

# MINIMUM ENERGY TRANSPORT ADAPTABILITY

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*Numquam aliud natura, aliud sapientia dicit.*





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# CONTENTS

<b>Glossary of Terms</b>	<b>ix</b>
<b>List of Acronyms</b>	<b>xi</b>
<b>List of Variables</b>	<b>xiii</b>
<b>List of Figures</b>	<b>xv</b>
<b>List of Tables</b>	<b>xix</b>
<b>Abstract</b>	<b>xxi</b>
<b>1 Introduction</b>	<b>1</b>
1.1 Transport energy consumption and the urban form . . . . .	1
1.2 Future transport energy constraints . . . . .	3
1.3 Transport energy adaptation . . . . .	4
1.3.1 Risk to transport energy constraints . . . . .	7
1.3.2 Travel adaptability surveying . . . . .	8
1.4 Contribution of this research . . . . .	10
1.5 Thesis organisation . . . . .	11
<b>2 Review of relevant fields</b>	<b>13</b>
2.1 History of cities . . . . .	13
2.2 Urban form and transport energy consumption . . . . .	15
2.3 Urban planning . . . . .	16
2.3.1 Land use planning . . . . .	17
2.3.2 Transportation planning . . . . .	17
2.4 Integration of land use and transport planning . . . . .	19
2.4.1 Urban simulation . . . . .	19
2.4.2 Fuel price vulnerability . . . . .	20

2.4.3	Transport energy reduction scenarios . . . . .	21
2.4.4	Minimum energy urban forms . . . . .	22
2.4.5	Transport energy in urban planning . . . . .	23
2.4.6	Accessibility . . . . .	24
<b>3</b>	<b>Theoretical background</b>	<b>27</b>
3.1	Energy auditing . . . . .	27
3.2	Energy modelling . . . . .	28
<b>4</b>	<b>Methodological review</b>	<b>31</b>
4.1	Accessibility . . . . .	31
4.2	Travel activity modelling . . . . .	36
4.3	Summary . . . . .	38
4.4	Modal energy intensity values . . . . .	38
<b>5</b>	<b>Method</b>	<b>41</b>
5.1	Minimum Energy Transport Adaptability (META) method approach . . . . .	41
5.2	Study area inputs . . . . .	47
5.2.1	Demographic data . . . . .	47
5.2.2	Origins . . . . .	48
5.2.3	Activity facilities . . . . .	48
5.2.4	Employment facilities . . . . .	49
5.2.5	Transport networks . . . . .	49
5.3	Constant inputs . . . . .	52
5.3.1	Minimum saturation values . . . . .	56
5.3.1.1	Activities . . . . .	57
5.3.1.2	Employment . . . . .	57
5.3.2	Mode ability . . . . .	59
5.3.3	Activity frequency . . . . .	60
5.3.4	Trip chaining factor . . . . .	61
5.3.5	Modal energy intensity . . . . .	62
5.4	META algorithm . . . . .	62
5.4.1	Origin-destination routes calculation . . . . .	62
5.4.2	Assign demography to origins . . . . .	65
5.4.3	Mode ability weighting . . . . .	67
5.4.4	Minimum energy mode assignment . . . . .	69
5.4.5	Activity frequency weighting . . . . .	71
5.4.6	Trip chaining factor weighting . . . . .	73
5.4.7	META minimum energy calculation . . . . .	75
5.5	META implementation . . . . .	77
5.5.1	List of META data sources . . . . .	77

<b>6</b>	<b>Case studies</b>	<b>81</b>
6.1	New Zealand Constant Inputs . . . . .	81
6.2	Christchurch . . . . .	88
6.2.1	Study area inputs . . . . .	93
6.2.1.1	Census data . . . . .	93
6.2.1.2	Origins . . . . .	93
6.2.1.3	Activity facilities . . . . .	94
6.2.1.4	Employment facilities . . . . .	96
6.2.1.5	Transport networks . . . . .	99
6.2.2	Christchurch META analysis results . . . . .	107
6.2.2.1	Mode ability results . . . . .	107
6.2.2.2	Trip rate results . . . . .	111
6.2.2.3	META minimum energy results . . . . .	111
6.2.2.4	META modal contributions . . . . .	113
6.2.2.5	META activity contributions . . . . .	117
6.2.3	Summary of Christchurch results . . . . .	121
6.3	Hamilton . . . . .	127
6.3.1	Study area inputs . . . . .	131
6.3.1.1	Census data . . . . .	131
6.3.1.2	Origins . . . . .	131
6.3.1.3	Activity facilities . . . . .	132
6.3.1.4	Employment facilities . . . . .	134
6.3.1.5	Transport networks . . . . .	137
6.3.2	Hamilton META analysis results . . . . .	144
6.3.2.1	Mode ability results . . . . .	145
6.3.2.2	Trip rate results . . . . .	149
6.3.2.3	META minimum energy results . . . . .	149
6.3.2.4	META modal contributions . . . . .	151
6.3.2.5	META activity contributions . . . . .	155
6.3.3	Summary of Hamilton results . . . . .	159
6.4	Discussion of case study results . . . . .	165
6.5	Consequences for other cities . . . . .	168
<b>7</b>	<b>Discussion</b>	<b>173</b>
7.1	Methodological assumptions and issues . . . . .	175
7.1.1	Age as travel determinant . . . . .	175
7.1.2	Travel time definition of mode ability . . . . .	176
7.1.3	Mode viability . . . . .	176
7.1.4	Home basis of trips . . . . .	176
7.1.5	Vehicle occupancy . . . . .	177
7.1.6	Trip chaining as an adaptive response . . . . .	177

7.2	Implementation assumptions and issues . . . . .	177
7.2.1	Mode ability . . . . .	178
7.2.2	Minimum saturation values . . . . .	178
7.2.3	Current levels of trip chaining . . . . .	179
7.2.4	Demography assignment . . . . .	179
7.2.5	Sensitivity analysis of constant inputs . . . . .	179
7.2.6	Quality of the study area inputs . . . . .	184
7.3	Model validation . . . . .	185
7.4	Future work . . . . .	186
<b>8</b>	<b>Conclusions</b>	<b>189</b>
	<b>Bibliography</b>	<b>191</b>
<b>A</b>	<b>Case study public transport route maps</b>	<b>203</b>
A.1	Christchurch . . . . .	203
A.2	Hamilton . . . . .	206
<b>B</b>	<b>Publications and conferences</b>	<b>207</b>
B.1	Peer reviewed journal papers . . . . .	207
B.1.1	Transportation Research Record: Journal of the Transportation Research Board, No. 2242 . . . . .	207
B.1.1.1	Review results . . . . .	217
B.2	Peer reviewed conference papers . . . . .	220
B.2.1	Institute of Professional Engineers New Zealand Transportation Group: 2011 Conference . . . . .	220
B.2.1.1	Review results . . . . .	237
B.2.2	Institute of Professional Engineers New Zealand Transportation Group: 2012 Conference . . . . .	238
B.2.2.1	Review results . . . . .	255
B.3	Conference presentations . . . . .	255

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## GLOSSARY OF TERMS

**Activity:** Occupation or pursuit, such as work, shopping or recreation that an individual engages in with some frequency. May not necessarily require travel. For use in modelling activities are usually classified into descriptive categories.

**Adaptive capacity:** The extent of transport energy adaptations that are possible within an area without loss of activity engagement. Adaptive capacity is a function of unconstrained energy consumption, land use patterns and transport systems.

**Destination:** Facility that has been selected for engaging in an activity; subset of all the facilities at which an activity might be conducted.

**Facility:** Location at which an activity might be conducted. For example, a book shop is a facility at which someone could engage in shopping.

**Geographical Information Systems (GIS):** systems designed to store, manipulate, analyse and present geographical data.

**Impedance:** A characteristic which acts to oppose flow. In transport networks impedance usually takes the form of distance, time or monetary cost.

**Land use pattern:** The layout of land uses within an urban area.

**Major Urban Areas (MUA):** Statistics New Zealand area with a population of over 30,000 people

**Mode:** Transport mode utilised when travelling to an activity. In the META model this is either Walk (WK), Cycle (CY), Public Transport (PT) or Private Vehicle (PV).



**Minimum transport energy:** The household transport energy consumption once all short term adaptations have been enacted. Minimum transport energy consumption is a function of land use patterns, available transport networks and the abilities and activity requirements of residents.

**Saturation:** The number of activity destinations that must be accessed to compensate for the effects of activity classification. For example, the classification *Shopping* will include a range of facilities including book stores, shoe stores, pharmacies, grocery stores, and so on. Consequently, a number of shopping facilities must be located to *capture* a general trip.

**Transport system:** The combined system of all transportation networks within an urban area.

**Trip chain:** A combination of trip legs from one location to another, which may contain intermediary stops as long as no stop is of greater than 90 minutes duration. For example, travel with one leg from work to a shop with a stop of 15 minutes then one leg to home would be classified as one trip chain with the ultimate purpose Home. Travel from work to a shop with a stop of 91 minutes then home forms two trip chains; the first for Shopping, the second for Home.

**Trip leg (trip):** One way course of travel from one location to another, with a single main purpose and no intermediary stops.

**Urban form:** General characterisation of the combination of *land use patterns* and *transport systems* within an area.

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# LIST OF ACRONYMS

<b>BITRE</b>	Bureau of Infrastructure, Transport and Regional Economics
<b>CAE</b>	Centre for Advanced Engineering
<b>CBD</b>	Central Business District
<b>DfT</b>	Department for Transport
<b>FHWA</b>	Federal Highway Administration
<b>GIS</b>	Geographical Information Systems
<b>IEA</b>	International Energy Agency
<b>MED</b>	Ministry of Economic Development
<b>META</b>	Minimum Energy Transport Adaptability
<b>MoT</b>	Ministry of Transport
<b>MUA</b>	Major Urban Area(s)
<b>NZHTS</b>	New Zealand Household Travel Survey
<b>NZTA</b>	New Zealand Transport Agency
<b>SACTRA</b>	Standing Advisory Committee on Trunk Road Assessment



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## LIST OF VARIABLES

Variable	Description	Units
$A_{m,i}$	Mode ability for person within age bin $i$ by mode $m$	minutes [ $min$ ]
$C_i$	Trip chaining factor for person within age bin $i$	
$CP$	Chain proportion: the number of trips made to non-home activities divided by the number of trips made to home	
$D_m$	Travel distance by mode $m$ along a particular network link	metres [ $m$ ]
$D_{j,a,n}$	Distance for household $j$ to reach activity $a$ destination $n$ once mode has been selected	metres [ $m$ ]
$D_{j,a,m,n}$	Travel distance for household $j$ to activity $a$ destination $n$ by mode $m$	metres [ $m$ ]
$E_j$	Minimum energy potential for household $j$	Annual GJ
$E_{j,a,n}$	Minimum energy potential for household $j$ to reach activity $a$ destination $n$	Annual GJ
$F_{a,i}$	Annual activity frequency of accessing activity $a$ for person within age bin $i$	$\frac{trips}{year}$
$H_k$	Number of households within census area $k$	

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Continued next page

Variable	Description	Units
$\mathbf{M}_{j,a,n}$	Mode by which household $j$ travels to activity $a$ destination $n$	
$\mu_{\mathbf{PT}}$	Energy intensity of travel by public transport (PT) mode	$\frac{GJ}{p-km}$
$\mu_{\mathbf{PV}}$	Energy intensity of travel by private vehicle (PV) mode	$\frac{GJ}{p-km}$
$\mu_{j,a,n}$	Modal energy intensity of travel for household $j$ to reach activity $a$ destination $n$	$\frac{J}{km}$
$\mathbf{N}_a$	Saturation value for activity $a$	
$\mathbf{P}_{i,k}$	Population within census area $k$ of age bin $i$	
$\mathbf{P}_{j,i}$	Population within household $j$ of age bin $i$	
$\mathbf{T}_m$	Travel time by mode $m$ along a particular network link	minutes [ $min$ ]
$\mathbf{T}_{j,a,m,n}$	Travel time for household $j$ to activity $a$ destination $n$ by mode $m$	minutes [ $min$ ]
$\mathbf{wA}_{j,m}$	Weighted mode ability for members of household $j$ by mode $m$	minutes [ $min$ ]
$\mathbf{wC}_j$	Weighted trip chaining factor for household $j$	
$\mathbf{wF}_{j,a}$	Weighted annual frequency of activity access for household $j$ to activity $a$	$\frac{trips}{year}$

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## LIST OF FIGURES

1.1	Hypothetical example of short term energy consumption responses to transport energy supply pressures . . . . .	6
4.1	Comparison of opportunity weighting functions commonly used in accessibility modelling . . . . .	34
4.2	Comparison of impedance functions commonly used in accessibility modelling . . . . .	35
5.1	Outline of the META method . . . . .	44
5.2	Example urban form: networks, destinations and quickest route to the closest post office by active modes and vehicle . . . . .	45
5.3	Walking network example with sample selected for graph representation	51
5.4	Example of saturation value calculation . . . . .	58
5.5	Cumulative distribution of walking trip duration for children of 5-9 years of age; 75 <sup>th</sup> percentile figure highlighted . . . . .	60
5.6	Schematic diagram of origin-destination routes calculation . . . . .	64
5.7	Schematic diagram of origin demography assignment . . . . .	66
5.8	Schematic diagram of mode ability weighting calculation . . . . .	68
5.9	Schematic diagram of minimum energy mode calculation . . . . .	70
5.10	Schematic diagram of activity frequency weighting calculation . . . . .	72
5.11	Schematic diagram of trip chaining factor weighting calculation . . . . .	74
5.12	Schematic diagram of minimum energy calculation . . . . .	76
6.1	Christchurch region: satellite communities proximate to Christchurch, Territorial Authority jurisdictions and major roads . . . . .	89
6.2	Christchurch city census Area Units, major roads and key outlying suburbs	90
6.3	Christchurch city population density at census Area Unit level, Key Activity Centres and Tertiary education facilities . . . . .	91
6.4	Christchurch topography and major roads . . . . .	92
6.5	Distribution of age at census Area Unit level in Christchurch, key areas highlighted . . . . .	93
6.6	Origin points used within the Christchurch analysis; inset shows detail	94

6.7	Density of non-education activity facilities in Christchurch at census Area Unit level . . . . .	95
6.8	Spatial distribution of Christchurch education facilities . . . . .	96
6.9	Frequency histogram of Christchurch employment opportunities at census Meshblock level . . . . .	97
6.10	Density of Christchurch employment opportunities at census Area Unit level . . . . .	98
6.11	Christchurch walking network overview . . . . .	99
6.12	Christchurch walking network detail . . . . .	100
6.13	Christchurch cycle network overview . . . . .	101
6.14	Christchurch cycle network detail . . . . .	102
6.15	Christchurch public transport network overview: route outline and effective speeds . . . . .	104
6.16	Christchurch public transport network detail: route specification and interface with walking network . . . . .	105
6.17	Christchurch private vehicle network overview . . . . .	106
6.18	Distribution of Christchurch walking mode ability . . . . .	108
6.19	Distribution of Christchurch cycling mode ability . . . . .	109
6.20	Distribution of Christchurch public transport mode ability . . . . .	110
6.21	Distribution of Christchurch annual trip frequency . . . . .	111
6.22	Distribution of Christchurch annual household META minimum transport energy consumption . . . . .	112
6.23	Distribution of public transport contribution to Christchurch annual household META transport energy consumption . . . . .	115
6.24	Distribution of private vehicle contribution to Christchurch annual household META transport energy consumption . . . . .	116
6.25	Distribution of Preschool travel contribution to Christchurch annual household META transport energy consumption . . . . .	117
6.26	Distribution of Primary/Intermediate school travel contribution to Christchurch annual household META transport energy consumption . . . . .	119
6.27	Distribution of Secondary school travel contribution to Christchurch annual household META transport energy consumption . . . . .	120
6.28	Distribution of Tertiary education travel contribution to Christchurch annual household META transport energy consumption . . . . .	121
6.29	Distribution of Medical/Dental travel contribution to Christchurch annual household META transport energy consumption . . . . .	122
6.30	Distribution of Personal business travel contribution to Christchurch annual household META transport energy consumption . . . . .	123
6.31	Distribution of Shopping travel contribution to Christchurch annual household META transport energy consumption . . . . .	124
6.32	Distribution of Social visits travel contribution to Christchurch annual household META transport energy consumption . . . . .	125
6.33	Distribution of Employment travel contribution to Christchurch annual household META transport energy consumption . . . . .	126

6.34	Hamilton region: communities proximate to Hamilton, Territorial Authority jurisdictions and major roads . . . . .	127
6.35	Hamilton city census Area Units, major roads and key outlying suburbs	128
6.36	Hamilton city population density at census Area Unit level, key shopping areas and major Tertiary education facilities . . . . .	129
6.37	Hamilton topography and major roads . . . . .	130
6.38	Distribution of age at census Area Unit level in Hamilton, key areas highlighted . . . . .	131
6.39	Origin points used within the Hamilton analysis, major roads shown . .	132
6.40	Density of non-education activity facilities in Hamilton at census Area Unit level . . . . .	133
6.41	Spatial distribution of Hamilton education facilities . . . . .	134
6.42	Frequency histogram of Hamilton employment opportunities at census Meshblock level . . . . .	135
6.43	Density of Hamilton employment opportunities at census Area Unit level	136
6.44	Hamilton walking network overview . . . . .	137
6.45	Hamilton walking network detail . . . . .	138
6.46	Hamilton cycle network overview . . . . .	139
6.47	Hamilton cycle network detail . . . . .	140
6.48	Hamilton public transport network overview: route outline and effective speeds . . . . .	142
6.49	Hamilton public transport network detail: route specification and interface with walking network . . . . .	143
6.50	Hamilton private vehicle network overview . . . . .	144
6.51	Distribution of Hamilton walking mode ability . . . . .	146
6.52	Distribution of Hamilton cycle mode ability . . . . .	147
6.53	Distribution of Hamilton public transport mode ability . . . . .	148
6.54	Distribution of Hamilton annual trip frequency . . . . .	149
6.55	Distribution of Hamilton annual household META minimum transport energy consumption . . . . .	150
6.56	Distribution of public transport contribution to Hamilton annual household META transport energy consumption . . . . .	153
6.57	Distribution of private vehicle contribution to Hamilton annual household META transport energy consumption . . . . .	154
6.58	Distribution of Preschool travel contribution to Hamilton annual household META transport energy consumption . . . . .	155
6.59	Distribution of Primary/Intermediate school travel contribution to Hamilton annual household META transport energy consumption . . .	157
6.60	Distribution of Secondary school travel contribution to Hamilton annual household META transport energy consumption . . . . .	158
6.61	Distribution of Tertiary education travel contribution to Hamilton annual household META transport energy consumption . . . . .	159
6.62	Distribution of Medical/Dental travel contribution to Hamilton annual household META transport energy consumption . . . . .	160



6.63	Distribution of Personal business travel contribution to Hamilton annual household META transport energy consumption . . . . .	161
6.64	Distribution of Shopping travel contribution to Hamilton annual household META transport energy consumption . . . . .	162
6.65	Distribution of Social visits travel contribution to Hamilton annual household META transport energy consumption . . . . .	163
6.66	Distribution of Employment travel contribution to Hamilton annual household META transport energy consumption . . . . .	164
6.67	Average META minimum energy within census areas versus residential density . . . . .	171
7.1	Census Area Units selected for sensitivity analysis . . . . .	181
7.2	Christchurch META minimum energy versus census Journey to Work (JTW) data . . . . .	186
A.1	Christchurch inner city bus routes . . . . .	204
A.2	Christchurch city bus routes . . . . .	205
A.3	Hamilton city bus routes . . . . .	206

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## LIST OF TABLES

4.1	Energy intensity values and source . . . . .	40
5.1	Matrix of example transport network in graph representation . . . . .	51
5.2	New Zealand Household Travel Survey (NZHTS) trip activity classifica- tions and descriptions . . . . .	54
5.3	NZHTS activity classifications, list of META activity classifications and mappings between activity classification schemes . . . . .	55
5.4	Trip activity classifications used in the US and UK national household travel surveys . . . . .	58
5.5	List of data sources for META study area inputs and New Zealand examples . . . . .	78
5.6	List of data sources for META nationally constant inputs and New Zealand examples . . . . .	79
6.1	Minimum saturation values calculated within New Zealand cities, sample size indicated in parentheses . . . . .	82
6.2	Overall minimum saturation values calculated for New Zealand cities, as used in the model, sample size indicated in parentheses . . . . .	82
6.3	Mode ability values calculated for New Zealand cities, sample size indicated in parentheses . . . . .	84
6.4	Education activity frequency values calculated for New Zealand cities, sample sizes indicated in parentheses . . . . .	85
6.5	Non-education activity frequency values calculated for New Zealand cities, sample sizes indicated in parentheses . . . . .	86
6.6	Trip chaining factor values calculated for New Zealand cities, sample sizes indicated in parentheses . . . . .	87
6.7	Effective speed by road type used in the Christchurch private vehicle network . . . . .	107
6.8	Weighted mode abilities in Christchurch Area Units . . . . .	108
6.9	Annual Christchurch household META minimum transport energy con- sumption . . . . .	113

6.10	Modal contributions to Christchurch annual household META minimum transport energy consumption . . . . .	114
6.11	Activity contributions to Christchurch annual household META minimum transport energy consumption . . . . .	118
6.12	Weighted mode abilities in Hamilton Area Units . . . . .	145
6.13	Annual Hamilton household META minimum transport energy consumption . . . . .	151
6.14	Modal contributions to Hamilton annual household META minimum transport energy consumption . . . . .	152
6.15	Activity contributions to annual Hamilton household META minimum transport energy consumption . . . . .	156
6.16	Effective radii and population for selected international cities (Demographia, 2012) . . . . .	172
7.1	Initial mean energy consumption values in sensitivity analysis . . . . .	181
7.2	Sensitivity analysis results . . . . .	183

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# ABSTRACT

IN THE FACE OF future transport energy supply constraints it is imperative that planners understand transport energy adaptability within cities. This thesis presents for the first time an analysis methodology for mapping the spatial distribution of limits to energy adaptability. Termed the Minimum Energy Transport Adaptability (META) method, it characterises urban areas, synthesising a situation in which households have enacted all viable transport energy adaptations. The output is an estimation of the minimum possible transport energy required by households in meeting their day-to-day activity requirements. The META method combines elements of energy engineering, accessibility modelling and transport activity modelling. The analysis makes use of national household travel surveys to define the frequency of activity access and ability to use modes at the national level, and study area GIS data for origins, facilities and transport networks. Two case studies have been investigated in New Zealand, the cities of Christchurch and Hamilton, and have shown that most residential areas in these cities do not limit the adaptive options available to residents. However, outlying areas, satellite towns and lifestyle properties consistently require large amounts of transport energy consumption and thus limit the ability of residents to adapt to future energy constraints. The META model enables, for the first time, the effects of future transport energy constraints to be mapped, visualised, quantified, and consequently considered in the planning process.

## CHAPTER 1

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# INTRODUCTION

In the face of future transport energy supply constraints it is imperative that planners understand transport energy adaptability within cities. This thesis presents for the first time an analysis methodology for mapping the spatial distribution of limits to energy adaptability. This chapter describes the links between urban forms and transport energy consumption, outlines future transport energy constraints, examines existing approaches to understanding transport energy adaptability and introduces the Minimum Energy Transport Adaptability (META) analysis methodology.

### 1.1 Transport energy consumption and the urban form

Energy, of one form or another, is essential for the transport of people and goods (Greene, 2004). Historically, this energy was provided by humans, animals or wind. The low price and ready availability of fossil fuels over the past century has resulted in an almost complete shift to oil as the primary source of energy for transport uses (Grübler, Nakićenović & Schäfer, 1993; Newman & Kenworthy, 1999). A study performed by Newman and Kenworthy (1999) based upon 1990 data for 26 North American and Australian cities shows 95% of trips to work are made by private motor vehicle or public transport. In New Zealand, 91% of national trips to work on the 2006 census day were made by motor vehicle or public transport (Statistics New Zealand, 2006). The shift to fossil fuel energy sources has enabled cities to expand rapidly into low density suburban patterns, termed *sprawl*, at a much greater rate than populations have

increased (Hall, 1997; Aßmann & Sieber, 2005). A study undertaken by Newman and Kenworthy (1989a) of 32 major cities throughout the world identified that urban area growth between 1960 and 1980 was 65%, while the mean increase in urban population over that time was 28%. Energy is not the only cause of changes in urban form, but energy has undoubtedly been a crucial permitting factor (Owens, 1986).

Urban form significantly influences travel and fuel consumption. The exact relationship has been the focus of many studies but, as a number of comprehensive meta-analyses have shown, few clear and consistent conclusions can be drawn. However density, accessibility and socio-economic variables are often identified as strong factors (Kenworthy, 1986; Newman & Kenworthy, 1989b; Anderson, 1996; Ewing & Cervero, 2001, 2010; Liu & Shen, 2011). This relationship is reviewed in more detail in chapter 2. The transport energy consumption pattern for a particular person or household is the product of (Keyes, 1982; Owens, 1986; Boussauw & Witlox, 2011):

- the need to participate in activities for example, education, shopping, employment and home;
- the spatial separation between facilities at which activities may be conducted; and
- the energy type and consumption rate associated with transport modes utilised.

Sprawling development patterns increase vehicle use, and hence fossil fuel consumption, through two mechanisms (Owens, 1986):

1. limiting the viability of non-car modes and
2. increasing the spatial separation of activities.

Travel modes are selected based upon a complex set of personal decisions; habitual behaviour, trip distance, travel time, safety and cost are known to be significant influences (Cervero & Radisch, 1996; Anable, 2005; Ewing & Cervero, 2010). The viability of non-car modes is reduced in environments subject to sprawl because residential density is too low to support high-frequency and well-connected public transport, and distances are too great for walking and cycling, modes which typically have a shorter range due to slower travel speeds (Naess, 1995; Camagni, Gibelli & Rigamonti, 2002). Additionally, increasing spatial separation of activities results in greater travel distances for trips by all modes, further increasing travel distances and hence energy consumption (Owens, 1986; Newman, Beatley & Boyer, 2009).

Consequently, not only are sprawled urban forms an outcome of cheap and available fossil fuels, continuous supplies of cheap and available fossil fuels are *required* for the transport systems of these urban forms to operate (Owens, 1986; Newman et al., 2009).

## 1.2 Future transport energy constraints

Petrol and diesel, both derived from oil, are the predominant sources of energy used by transportation systems. In 2009 62% of global oil production was used for transport (International Energy Agency (IEA), 2011). Globally, fuels derived from oil accounted for 93.5% of 2009 total transport energy consumption, while for New Zealand in 2010 this figure was 99.3% (IEA, 2011; Ministry of Economic Development (MED), 2011).

Oil is by its nature a finite resource. Consequently, there are geological limits upon both the total global oil supply and possible rates of production (Benes et al., 2012). There is some point at which global oil production will reach a maximum, popularly termed “peak oil”, after which time there will be continuous decline in supply (Krumdieck, Page & Dantas, 2010). Numerous geologists and researchers have estimated dates at which this maximum will be reached, for example, Mohr (2010) identified 26 expert estimates of peak year ranging from 1996 to 2048, while Krumdieck et al. (2010) applied a risk analysis approach, building a probability distribution around existing estimates which indicates likely supply under selected risk scenarios. This distribution indicates a 50% probability of peak before 2012 and a 97% probability of peak before 2020 (Krumdieck et al., 2010). The comprehensive oil supply model developed by Mohr (2010) produced estimates of peak year ranging from 2005 to 2019, depending upon estimates and assumptions regarding interactions within the model. The Bureau of Infrastructure, Transport and Regional Economics (BITRE) (2009) performed an extensive analysis of historical data and future petroleum geology outcomes and arrived at the conclusion that global conventional oil production reached its maximum value in 2006. However, production of non-conventional oil sources, such as heavy, deep water, tar sand and oil shale derived oils, is currently increasing, with the result that net global oil production is in a plateau phase (BITRE, 2009). The point of maximum production for conventional *plus* non-conventional oil sources is expected to occur around 2016 (BITRE, 2009). After this point the global supply of oil will be in continuous decline. Regardless of the exact year of maximum production it is apparent that there is a high probability of continuous supply declines from 2020 onward. Benes et al. (2012) expect that tightening supply, coupled with supply declines, will result in significantly increased prices. Furthermore, political and economic factors

are likely to impact upon the decline profile, which could conceivably range from smooth year-on-year reductions in supply with price increases to a situation of sharp and unpredictable changes in price and availability (Owens, 1986; Newman et al., 2009). These reductions will not be a product of consumer choice or preference, but of increasing scarcity from the supply side. Consequences for the transportation sector, and particularly private transport, are likely to be significant and will be exacerbated by two main factors (Krumdieck et al., 2010; Rickwood, 2010; de Almeida & Silva, 2011):

- transport systems are highly dependent on crude oil, and there are no other energy sources currently available that possess the ability to fill the gap between the amount of energy available into the future and the amount of energy that transport systems require;
- private transport is the most discretionary and most easily reduced of all the uses that society has for oil. It is thus likely to be subject to greater supply reductions than those seen in the overall system.

There is at present no method for understanding how the transport systems of urban forms will perform under situations of reduced fuel availability and continuous supply decline (Newman et al., 2009).

### 1.3 Transport energy adaptation

Residents will, of necessity, attempt to adapt their transport energy consumption to match available supply, but adaptive measures might not be viable, or involve unfavourable impacts (Krumdieck et al., 2010). There are three short term adaptations available to reduce the transport energy intensity of travel to engage in an activity (Krumdieck et al., 2010):

1. combining travel to multiple activities into a single trip chain;
2. using a more efficient vehicle or shifting to a less energy intensive mode; and
3. selecting activity destinations that require less travel, including participating without travel.

All three adaptations are measures which reduce the energy intensity of travel while maintaining activity participation. If travel to an activity cannot be adapted,

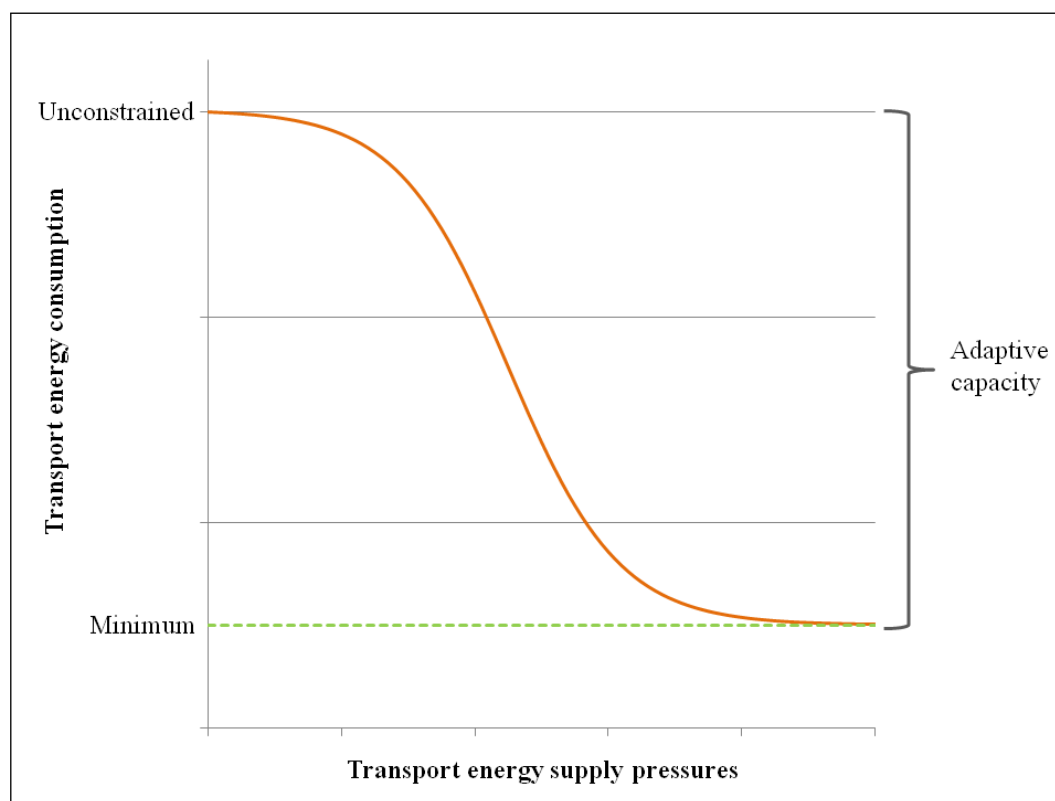


participation in that activity may have to be forgone, which will severely impact upon personal and household well-being. The ability to adapt depends upon behaviour and the land use patterns and transport systems of the built urban form (Krumdieck et al., 2010). Trip chaining will result in reduced intensity only where activity facilities for different activities are near each other, or facilities are located with such density that routes coincide; for example, shopping facilities near places of employment or between places of employment and the home. Change in activity destinations requires a high enough density of activity facilities that an equivalent facility exists that requires less travel to reach. It is possible to participate in only a limited set of activities without travel, or there may be other requirements, such as high-speed internet for a person to engage in employment from home. The use of a more efficient vehicle may require the purchase of a new vehicle or careful use of existing household vehicles to ensure the most efficient vehicle is used wherever possible. Shifting to a less energy intensive mode requires appropriate infrastructure that is both available and viable. For example, footpaths or cycle lanes connecting origins with potential facilities, or public transport routes within a walkable distance of the point of trip origin and potential facilities, and with a reasonable service timetable for the activity being conducted. Greater reductions in energy intensity can be achieved where multiple adaptations can be combined, for example a public transport hub that is close to employment, with shopping, social and personal business facilities all located nearby might allow a public transport trip and multiple walking trips to be substituted for a number of car trips. Each of these measures might involve negative impacts, such as a reduction in product choice if using a closer shop, or reduced flexibility when using public transport. Transport energy supply pressures will force adaptive responses and reduce energy consumption from what would be observed in unconstrained situations. However, the extent of energy adaptations possible for a household is limited by the land use patterns and transport systems of the urban form. There is consequently a lower limit on energy consumption, as outlined in figure 1.1. Two terms are now defined:

**Adaptive capacity:** the extent of transport energy adaptations that are possible within an area without loss of activity engagement. Adaptive capacity is a function of unconstrained energy consumption, land use patterns and transport systems.

**Minimum transport energy:** the household transport energy consumption once all short term adaptations have been adopted. Minimum transport energy consumption is a function of land use patterns, available transport networks and

the abilities and activity requirements of residents.



**Figure 1.1:** Hypothetical example of short term energy consumption responses to transport energy supply pressures

Different residential areas might have the same unconstrained energy consumption but differ in their minimum energy consumption, and hence adaptive capacity, as their respective land use patterns and transport systems enable different extents of adaptation. Residents in an area with a lower minimum transport energy consumption are less likely to lose activity participation under future energy supply constraints. Over the long term there are two possible adaptive responses: purchasing a more efficient vehicle or moving residence to an area with a lower minimum transport energy consumption. A long term consequence of energy supply constraints will be a decline in population in areas that limit transport energy adaptations.

Previous oil supply events have highlighted the differences in adaptive capacity between various urban forms. For example, the energy crises caused by the 1973-74 oil embargoes saw many Americans choosing to forgo activities, while in Europe there were considerable increases in public transport use (Pisarski & Terra, 1975). In many American cities the built urban forms simply did not allow the majority of residents to

adapt, indicating a lower adaptive capacity in American cities than in European cities (Newman et al., 2009). The effect of variations in land use patterns and transport systems can also be significant within cities. Residents in the urban fringe of some Australian cities spend up to 40 percent of their income on transport, most of this by private car (Newman et al., 2009). This indicates a significant lack of alternatives for these residents and implies a lower adaptive capacity. In Melbourne, Currie et al. (2009) investigated the concept of *forced car ownership*, where low-income residents are forced to own and operate cars because no other transport options are available. Without changes to land use patterns or transport systems the adaptive capacity in these areas will be negligible, and it is likely to become impractical to live in these areas in the face of future energy constraints (Fishman & Brennan, 2010). An understanding of the limits to transport energy adaptation is crucial for understanding how different urban areas will respond to the pressures of reduced fuel availability and continuous supply declines (Rickwood, 2010).

The literature, as reviewed in Chapter 2, presents a number of approaches for assessing the combined effect of transport systems and land use patterns. Such an assessment is necessary to understand transport energy adaptations, although none of the reviewed studies focuses on energy adaptability. There is a limited selection of studies that consider the energy implications of land use patterns and transport systems, either in terms of the energy risk to residents or for the design of energy-optimal urban form layouts in new developments. These approaches are also reviewed in Chapter 2. To the best of the author's knowledge there are only two studies which attempt to understand the effects of transport energy adaptability in the face of future energy constraints. Both of these approaches have been designed and developed by the Advanced Energy and Materials Systems Laboratory at the University of Canterbury and are described in the following sections.

### 1.3.1 Risk to transport energy constraints

Krumdieck et al. (2010) developed the Risk to Energy Constrained Activity-Transportation Systems assessment model (RECATS) to understand the future implications of transport energy constraints on different proposed urban development patterns.

The researchers first used a range of expert predictions for future conventional oil supply to build a probability distribution for oil availability in future years. This distribution gives the probability that a certain oil supply is able to be met in a given year. For example, in 2035 there is only a 50 percent probability that a supply value

of 19 billion barrels of oil per year will be available. The oil supply in 2005 was approximately 28 billion barrels per year, so this equates to a 50 percent probably of a 30 percent reduction in supply by 2035. The method then investigates the performance of a given urban transportation system under this future reduction. Trips are assigned an *essentiality* rating, with more essential trips exerting a greater impact upon residents if they are adapted or forgone. The model accepts a standard travel demand pattern, with trips classified into short, medium and long distance bins for each mode, and assumes an essentiality distribution within these bins. The operator defines limits specifying the extent to which the fuel constraint adaptation options of combining activities, changing activity destination and shifting mode are possible. The model uses Monte Carlo simulation to adapt or eliminate trips until the input fuel constraint is met. Risk is attributed based upon the number and essentiality of trips that were adapted or lost. If the constraint could be met with adaptive measures alone there is a lower risk than if trips were lost. The model was used to compare three future development options, Concentration, Consolidation, and Dispersal, and a ‘business as usual’ scenario in Christchurch for the year 2041, as presented in the Greater Christchurch Urban Development Strategy. The results indicated that the Concentrated development pattern, with increased inner-city density but limited urban sprawl and satellite town growth, produced the lowest risk profile.

The RECATS method represents the first research effort to quantify the impact of transport fuel constraints, consequent adaptations and possible loss of activity participation. It showed that urban forms have the potential to place users at risk if they limit adaptability. The method, however, operates at the strategic level, and presents risk as a generalised negative only, without calculating the spatial distribution of risk. Furthermore, the design and application of the method mean that it is unable to highlight specific interventions that would reduce risk to current or future urban forms.

### 1.3.2 Travel adaptability surveying

Watcharasukarn, Krumdieck, Green and Dantas (2011) and Watcharasukarn, Page and Krumdieck (2012) developed a game platform survey tool, called the Travel Activity Constraint Adaptation Simulation (TACA Sim), to collect information on transport responses to fuel price rises. The survey is divided into two main parts: a travel demand survey, and a travel adaptability survey.

During the first part of the survey the participant provides demographic informa-

tion and details about household vehicles. The interactive survey then takes the user through every day of the week and collects the following information for each trip:

- mode utilised
- vehicle used (if applicable)
- trip purpose
- trip essentiality
- departure and arrival time
- travel distance, and
- whether the participant has any other option for making the trip.

This section of the survey contains two elements that are novel in the field of travel surveying: first, questioning trip essentiality; and second, assessing if there are other options for making the trip. The purpose of the latter question is to assess the *adaptive potential*, which is defined by the researchers as the potential to change mode or participate without travelling to reduce the energy intensity of a particular trip.

The second part of the interactive survey simulates an escalating price rise situation to evaluate adaptive responses. The simulation represents three weeks of travel, the first with fuel at the then-normal price of \$1.64 per litre, then on Monday of the second and third weeks the price rises to \$5.64 per litre then \$9.65 per litre, respectively. For the first week the user is presented with their unconstrained travel information of the corresponding day. Trips can be added, deleted, or changed each time the activity arises. Possible trip modifications are: changing mode, changing destination, curtailing trips, moving residence location and participating in the activity without travelling. The survey program keeps track of fuel use, allowing participants to refuel their vehicle at any time but requiring they refuel the vehicle when empty. Responses were entirely dependent upon the participants' experience and perception of the current alternatives. For example, a respondent may choose to carpool rather than taking the bus because of a previous bad experience or ignorance of the bus schedule.

[Watcharasukarn et al. \(2012\)](#) present the results for 90 respondents from the University of Canterbury in Christchurch, New Zealand. Respondents included academic staff, general staff and students. Overall, the number of car trips was reduced by 50% in the medium price scenario and 75% in the highest price scenario. Most of this adaptation was through mode shifting to walking, cycling and public transport modes,

but changing destination, rearranging trips and combining activities were also measures commonly selected to reduce fuel use under increasing price. Neither combining destination shifting with mode shifting nor combining trips into chains were popular options, with about 1% of respondents selecting to enact each. Participation without travel varied across respondent groups, with students reporting a much higher ability to do so than staff. At the end of the simulation, 6% of respondents had chosen to move residence to a new location closer to the university, suggesting future negative property value impacts for locations that require long-distance car travel to access activities.

The TACA Sim survey has shown that people have the potential to adapt their transport energy consumption when fuel prices rise. It also highlights that adaptive capacity varies across different groups of people and is influenced by the perception of alternative modes. Unfortunately, sample sizes are too small to allow spatial analysis of the urban form factors that influence adaptive capacity. The results of TACA Sim show that people can and will adapt their travel when faced with fuel constraints. Furthermore, as described in figure 1.1, the extent of adaptation enacted is dependent upon the amount of price pressure. However, the work does not examine limits to adaptation that are exerted by the urban form.

## 1.4 Contribution of this research

There is a need for modelling capabilities to quantify transport energy adaptability within urban areas such that future impacts of energy supply decline can be understood and mitigated. Although the RECATS and TACA Sim models both approach the problem of transport adaptability to future energy constraints, neither tool identifies the specific urban form characteristics that limit transport energy adaptability. This thesis presents an approach to characterising the spatial distribution of limits to transport energy adaptation within an urban area, termed the META method. The META method estimates the minimum transport energy theoretically required by households to meet their current day-to-day activity requirements by assuming that, for travel to each activity, the closest facility is chosen and the lowest energy mode viable for the trip is used. The META characterisation of an urban area is a function of land use patterns, transportation systems, and the activity requirements and physical abilities of residents. It is not a function of unconstrained travel behaviour, but of the built urban form when inhabited by a given population. Residents in areas with low META energy requirements are less likely to lose activity participation under future energy supply constraints. Conversely, areas with high META energy requirements are those

that provide few adaptation options and residents will face higher exposure to the negative effects of future transport energy supply constraints.

## 1.5 Thesis organisation

This thesis presents a new method for urban form analysis. Consequently, the background and literature review are split over three chapters; the first of which sets the scene and describes existing approaches of integrated urban analysis, the second presents the theoretical underpinnings of the model and the third describes existing methodologies upon which the method builds. The remaining chapters describe the META method, present case studies to which the method has been applied, discuss issues and assumptions of the methodology, and conclude the thesis. In detail, the thesis is structured as follows:

- Chapter 2:** a review of relevant fields and literature, which identifies a number of approaches for assessing the combined effects of transport systems and land use patterns necessary to understand transport energy adaptation.
- Chapter 3:** a description of analysis techniques common in energy systems engineering that underpin the META methodology, primarily energy auditing and building energy modelling.
- Chapter 4:** a detailed review of the specific modelling approaches of accessibility analysis and activity modelling, which form a basis for the theoretical model.
- Chapter 5:** explains the theoretical methodology for characterising the META minimum energy consumption in any given urban area, including data requirements and examples of New Zealand sources, and describes the method's implementation.
- Chapter 6:** an application of the META methodology to New Zealand and the results of two case studies: the cities of Christchurch and Hamilton.
- Chapter 7:** discusses the assumptions and issues involved in the theoretical method and implementation of the method, and also presents future planned improvements to both aspects of the model.
- Chapter 8:** discusses the key contributions of this thesis to the field of urban analysis and reiterates the urgent need for energy considerations in urban planning.





## CHAPTER 2

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# REVIEW OF RELEVANT FIELDS

Despite the importance of transport energy adaptability in the face of future energy supply constraints, the scientific literature sheds little light on the issue. This chapter outlines the historical development patterns of cities, discusses the literature linking transport and energy consumption within urban forms, then introduces and summarises the fields related to urban planning which influence transport energy adaptability. It concludes by reviewing research that is conceptually or methodologically beginning to approach the problem of transport energy adaptability.

## 2.1 History of cities

A history of cities sheds some light upon the application of urban planning fields, and the reasons behind urban development that has led to cities with high energy requirements and low adaptability. [Newman and Kenworthy \(1999\)](#) outline the evolution of city forms throughout history as a product of transport, cultural and economic forces, which is summarised in the remainder of this section.

City development has primarily been defined by changes in technology coupled with the effect of *travel time budget constancy*, which is an expression of the observation that humans tend to spend 60 minutes per day on travel ([Marchetti, 1994](#); [Newman & Kenworthy, 1999](#)). This property has been observed in numerous cities ([Newman & Kenworthy, 1999](#)), across various levels of wealth ([Schafer, 1998](#)), degrees of industrialisation and differences in cultural norms ([Robinson, Converse & Szalai, 1972](#)), urban or rural locality ([Tanner, 1961](#)), and remained stable in the United Kingdom for 600 years ([Standing Advisory Committee on Trunk Road Assessment \(SACTRA\)](#)),

1994).

### **The Walking city**

The first cities were settled in the Middle East between 10,000 and 7,000 years ago, and little variation in the general size or layout of cities was seen until the middle of the nineteenth century. This form was defined by two factors: the predominance of walking as a transport mode and the 60 minute travel time budget. In consequence the walking city was typically five kilometres in diameter, corresponding to a 25 minute walk from periphery to centre. It possessed relatively high residential densities of 100 to 200 people per hectare, high levels of land use mix, narrow streets and an organic form that moulded to the landscape. Many cities still contain high density walking city elements in their core.

### **The Transit City**

From about the 1860s onward growing population and industry started to place pressure on walking cities. However, the emerging technology of public transport enabled cities to continue to grow, if at lower density, while remaining within the bounds of the 60 minute travel time budget. Development based around rail lines tended to result in small pedestrian scale cities around stops, while tram lines produced linear development along corridors. In both cases medium density mixed use areas were formed along transport routes. Transit cities could now spread up to 20 or 30 kilometres, and featured densities of 50 to 100 people per hectare. The centre, where rail and tram lines met, produced areas of very high activity density. Most American, Australian and New Zealand cities were formed during this era, and still retain elements of the transit city (Newman, Bachevalier & Chapman, 2005).

### **The Automobile City**

Since the advent of the motor car, but particularly since World War II, the car and public bus have defined cities. The car made it possible for cities to grow in every direction. Given the higher travel speed of cars, cities could grow up to 100 kilometres in diameter while residents could remain within the travel time budget (Demographia, 2012). The car meant that people no longer had to live near their destinations. In reaction to the pollution, crowding and health issues experienced in industrial cities, town planners started to separate residential and business centres through zoning. This further increased travel requirements. Densities in the automobile city are typically around 10 to 20 people per hectare.

Cities in North America, Australia and New Zealand have all developed along the lines of the automobile city, despite retaining elements of walking and transit cities at their cores (Newman & Kenworthy, 1999; Newman et al., 2005). The automobile city produces high levels of dependence on private vehicles, due to low density residential development and zoning that segregates people and activities beyond the capabilities of active modes and public transport to connect them.

## 2.2 Urban form and transport energy consumption

Numerous studies have assessed the transport energy implications of urban form. However, the literature presents few clear and consistent conclusions. Newman and Kenworthy (1999) identify a significant inverse relation between density and transport energy consumption, although this finding is often debated (e.g., Owens, 1995; Mindali, Raveh & Salomon, 2004). Boarnet and Crane (2001) use several case studies to indicate that the price of travel is a stronger predictor of transport energy consumption than density, while Gordon and Richardson (1997) identify that if fuel prices are taken into account, density has a relatively limited effect upon transport energy consumption.

In a Brazilian study of 27 state capitals and 184 urban areas with more than 200,000 inhabitants da Silva, Costa and Brondino (2007) found that urban sprawl increased transport energy consumption. Within state capitals the urban density and the ratio between the longest distances in the east-west and north-south directions had the strongest influences on energy consumption. In urban areas with over 200,000 inhabitants these variables were strong predictors, but income and levels of employment were more influential.

Rickwood and Glazebrook (2009) compared the use of public transport for travel to work and density at the micro level, rather than city or urban area level, as other studies have done. They found increasing public transport mode share with residential density and proximity to Central Business Districts (CBD)s in Australian cities. However, they also identified that the strength of these relationships lessens as more complex measures of urban form and access to public transport are introduced into the analysis. This suggests that local area density and distance from the CBD are simply useful proxies for public transport based accessibility.

Although they do not focus particularly on energy, Ewing and Cervero (2001) analysed more than 50 empirical studies linking travel and urban form and computed overall travel elasticities for a number of variables. They reported the following: trip frequencies are primarily a product of socio-economic characteristics; trip lengths are

primarily a function of the built environment; mode choices depend upon both built environment and socio-economic factors, although they probably depend more upon the latter; and the built environment is a much more significant influence for total annual time and distance of vehicle travel than are other factors. [Ewing and Cervero \(2010\)](#) updated this work and considered a far greater number of empirical studies, many of which had been published since the first meta-analysis. They found that destination accessibility has the highest elasticity for overall vehicle travel, followed by the distance to CBD, then design metrics such as intersection density and street connectivity. The study further identified that, once other variables were controlled, population and job density both featured low elasticities in relation to vehicle travel. The highest elasticities relating to active mode use are found for intersection density, jobs-housing balance, and distance to stores. However, population and job density have low elasticities. The highest elasticities for mode share and frequency of trips by public transport are found for accessibility to public transport, network variables and the land use mix. Similarly, population and job density present low elasticities for public transport. The authors summarise that although density is a weak predictor when other factors are controlled, it is an intermediate variable that is, in many cases, associated with increases in destination and public transport accessibility, network connectivity and intersection density, and land use mix.

## 2.3 Urban planning

Urban planning, often simply referred to as *planning*, is a general term for public policy disciplines that aim to shape, order and regulate towns and cities ([Taylor, 2010](#)). It draws upon elements of engineering, architecture, and social and political concerns. Urban planning significantly influences energy adaptability. Not only have planning decisions largely defined cities as built today, planning will also significantly influence the available responses to energy issues.

The main branches of urban planning with which this work is concerned are *land use planning*, which balances local objectives and regional goals to designate and allocate land uses through legal and political decision making, and *transportation planning*, which aims to assess, evaluate, design and site transport infrastructure ([Schultz, 2007](#); [Shiftan, Button & Nijkamp, 2007](#); [Pincetl, 2010](#)). Combining the two fields is a common theme in planning theory but surprisingly, given their importance for city development, the two fields are typically not well connected in practice (e.g., [Stead, 2003](#); [Curtis, 2005](#)). The following sections describe transport and urban planning

fields in detail, and the final section of the chapter reviews approaches which integrate the fields to improve urban planning outcomes, and have the potential to begin to understand energy adaptability.

### 2.3.1 Land use planning

Simply defined as the *planning of the use of land*, land use planning entails interactions between levels of government and various markets, including land use markets, housing markets and labour markets (Priemus, Button & Nijkamp, 2007). Land use planning in the modern sense developed as a way to mitigate the impacts of industrial cities, and in particular air pollution, congestion, noise and lack of open space. Today, land use planning contains many theoretical elements such as:

- urban dynamics, which qualifies movements, forces and patterns within urban areas,
- the analysis of legal, political and institutional frameworks related to planning,
- studies of the implications of land use decisions, such as growth management policies, and
- urban network views of urban areas and interconnections.

Methods common to applied branches of land use planning usually take an economic or socially-based approach, for example, models to generate and allocate urban activities upon the basis of core employment activities within an area.

Modelling approaches that include transport elements are starting to become accepted in some countries. In the United Kingdom, Accessibility Statistics are computed at the national level. These statistics show, for example, the number of employment opportunities within 20 minutes of a local government area. These statistics provide a database with the intention of informing planners and assessing the effects of land use policy over time (Department for Transport (DfT), 2011).

### 2.3.2 Transportation planning

The field of transportation planning deals with the ways in which governments at various levels try to ensure transportation effectively and efficiently moves people and goods (Shiftan et al., 2007). Transportation planning shapes urban form, affects economic vitality, and impacts quality of life, with the goal of meeting wider social objectives.

Challenges posed on transportation planning have grown continuously over the years due to rising congestion, concerns with environmental impacts, enhanced awareness of safety and increasing complexity of travel patterns. The field of transportation planning deploys a wide range of analytical tools, initially to analyse the effects of various factors on travel behaviour, and then to find a suitable balance to obtain efficient and socially and environmentally viable transport solutions.

Transportation planning initially developed with the interstate highway systems in North America in the 1950s and 1960s, defining models of traffic assignment with the goal of specifying how many highways were required and where they were to be built. The focus of transportation planning shifted toward urban transport planning in the 1970s to address growing problems of congestion and air pollution within cities, and because of limited space for highway expansion. Models for understanding travel behaviour were developed in an attempt to forecast future travel demands, and thus better plan infrastructure. Further work was done to understand the possible responses of people to transport policy changes, such as congestion pricing, by including elements of travel activity patterns.

The vast majority of transport planning in urban areas is done using the four-step modelling procedure, a method developed in the late 1950s which has only received incremental refinement since (Stopher, Hartgen & Li, 1996). The method uses aggregate data about sub-regional areas, termed traffic analysis zones (TAZs), to estimate travel on present and proposed transport networks. The procedure consists of four steps (Stopher et al., 1996):

1. **Trip generation:** land uses are used to define trip ends generated in each TAZ,
2. **Distribution:** origin-destination pairings are produced given the trips from the previous step, defining the overall trip patterns of the region,
3. **Mode choice:** splits the trips between origins and destinations by mode of travel,
4. **Assignment:** trips are assigned to the relevant network, including for occupancy and possibly time-of-day factors.

In some applications a feedback of speeds and congestion from the assignment step to the trip distribution step is carried out. Although the four step model is widely used, and even institutionalised, in literally thousands of applications, it has also generated much criticism and controversy (Stopher et al., 1996). Common criticisms of

four step modelling include its ignorance of travel as a derived demand, inadequate specification of the interrelationships between travel and activity participation, and inability to meaningfully incorporate active modes given the size of TAZs (Recker, McNally & Root, 1986; Stopher et al., 1996; Kuzmyak, 2012). Models with an activity basis have gone some way towards addressing the first two criticisms, although they are still not widely used in practice.

## 2.4 Integration of land use and transport planning

As noted previously, despite often being presented within planning theory as integrated fields, land use and transport planning are typically not well integrated in practice (Stead, 2003; Curtis, 2005). True integration at all levels is crucial, as land use patterns, in the form of activity locations and residential densities, are strong determinants of the requirement to travel and of both transport energy consumption and adaptability (Newman & Kenworthy, 1999; Krumdieck et al., 2010). This section summarises studies and approaches which have started to combine the effects of land use and transport in urban analysis, and hence have the potential to understand energy adaptability. A limited selection exist of studies that consider the energy implications of land use patterns and transport systems, either in terms of the energy risk to residents or for the design of energy-optimal urban form layouts in new developments. To the best of the author's knowledge there are only two studies which attempt to understand the effects of transport energy adaptability in the face of future energy constraints. Both of these approaches have been detailed in chapter 1. However, none of these integrated approaches is widely used in practice.

### 2.4.1 Urban simulation

Microsimulation is an increasingly popular analysis technique for understanding highly detailed transport interactions between agents, for example, pedestrian movements through a train station which are affected by train arrivals and departures, time of day, day of week and so on. Microsimulation combines physical assumptions with behavioural modelling to understand and visualise these detailed interactions. Urban simulation is a form of microsimulation that models transport behaviour, land use behaviour and the interaction between the two (Waddell & Ulfarsson, 2004). The UrbanSim model, developed by Waddell et al. (2003), is a model intended to aid policy makers in understanding the effects of different policy options. For example,



the implementation of a metropolitan urban boundary will encourage higher densities and increases in property prices within an urban area; while a new highway through an area will attract future growth and influence residential location. The relevance of urban simulation models to transport adaptability is that the approaches of such models have the potential to include energy constraints as a factor. The models present a framework that could allow estimation of what may occur to transport systems and property prices as transport energy constraints progress. This would, however, require highly detailed information about behavioural responses to transport energy constraints and reductions, which do not exist at present. The models have a strong basis in accessibility - a concept that will be defined in more detail in section 2.4.6 - and might also be used to prototype and test the accessibility, and potentially the transport energy adaptability, of new developments.

### 2.4.2 Fuel price vulnerability

Oil price rises experienced since 2005 spurred interest in understanding how “the socio-economic and housing effects of rising fuel costs may be distributed across cities, especially the dispersed and car-dependent metropolitan regions of North America and Australia” (Dodson & Sipe, 2008, p. 378). To this effect, Dodson and Sipe (2008) developed the Vulnerability Assessment for Mortgage, Petrol and Inflation Risks and Expenditure (VAMPIRE) assessment methodology, which uses census data on car dependence, income and mortgage tenure to produce a vulnerability index that can be mapped and viewed spatially. Car dependence is defined as the combination of car ownership and use of a car for travel to work on the census day. The method scores each census unit depending upon its percentile rank within each of the variables, then sums the scores to produce the VAMPIRE index. Results for major Australian cities show that “many outer suburban households are more exposed to [fuel] price pressures because of their combined mortgage exposure, modest incomes and high car dependence” (Dodson & Sipe, 2008, p. 396). These households are likely to “experience high levels of socio-economic stress” during periods of fuel constraint and price rises (Dodson & Sipe, 2008, p. 397). Although displayed spatially, the method is not sensitive to spatial factors; it does not account for the location of potential activity facilities or the design and location of transport systems. Nor does the analysis highlight specific interventions or allow testing of proposed land use or transport system changes.

Building on the methods developed in the VAMIPRE analysis, Fishman and Brennan (2010) developed an oil vulnerability index that uses results from the Victorian



Integrated Survey of Travel and Activity (VISTA). The indicator is calculated with a similar method of percentile ranking, using survey results for fuel use, average personal income and modal split for all trips. The study showed similar results to the VAMPIRE analysis, with the CBD and adjacent areas exhibiting low vulnerability and low density suburbs on the fringes of the city exhibiting extreme vulnerability. Similarly to the VAMPIRE index, the metric does not suggest interventions or allow testing of proposed land use and transport changes.

The fuel price vulnerability assessments described above are useful for indicating which areas of a city are vulnerable to fuel price rises, but fail to explain the underlying causes of this vulnerability and what could be done to reduce it.

### 2.4.3 Transport energy reduction scenarios

Two studies, other than the RECATS study presented in chapter 1, have used future scenarios of transport energy availability to assess the risks to transport systems and future urban form development patterns. However, neither of these tools assesses transport energy adaptability.

Vanderschuren, Lane and Wakeford (2010) developed four scenarios of future energy availability up to 2030 for South African transport systems and assessed current levels of transport demand for road, rail and air transport. The researchers then reviewed measures that might have the potential to reduce future transport energy demand, making assumptions with regard to the rate of uptake and predicted future effectiveness of the options. The study reported that road based interventions alone were sufficient to reduce demand under the most optimistic supply projection, while all mode specific measures, plus mode shifting, were insufficient under the most pessimistic supply projection. The researchers conclude that although it is possible to meet the supply shortfall under most scenarios, action must be taken soon to ensure a smooth transition.

Wight and Newman (2010) outlined three likely global events resulting from future transport energy constraints and proposed three indicative urban development scenarios as potential measures to respond to these events. The researchers then assessed the combinations of event and development scenario in a risk management exercise. The likely transport energy events were defined by the researchers to be: sudden critical supply interruption, volatile price fluctuations and/or intermittent supply disruptions, and progressive price rises with diminution of supply. The proposed future development scenarios responding to energy events were:

- **Ruralised sprawl** - where most future development occurs on the urban fringe and is designed to be as self-sufficient in food as possible.
- **Centralised concentration** - where most future development is directed into the CBD area at very high intensities.
- **Decentralised concentration** - where most future development is directed into a number of centres distributed along transit routes, in medium density, mixed use centres.

The risk analysis assessed the likelihood of each oil event, then the impacts upon the development scenarios under each event. The study identified that patterns of ruralised sprawl are at highest risk under all events, while decentralised concentration was identified as the preferred option to minimise risk. Further analysis also estimated that the costs to both residents and government under a decentralised concentration scenario were lower than under a ruralised sprawl scenario.

#### 2.4.4 Minimum energy urban forms

Keirstead and Shah (2011) developed an optimisation tool for designing minimum energy urban layouts considering both the transport and building sectors. The approach divided urban energy consumption into four components:

- **City form** including buildings, transport and resource distribution networks;
- **Function** in terms of the use of infrastructure;
- **Energy supply system**; and
- **Life-cycle impacts** of materials required to build capital stocks.

The model is built upon optimisation-based sketch models, commonly used in the field of operations research. Its inputs are the spatial description of the development area, a list of aggregate activity demands and a specification of the available building types and transport modes. The outputs are located buildings and activities, transport network infrastructure and indicative flows and estimated costs, energy consumption and carbon emissions. The model was assessed by applying it to a proposed “eco-town” development in the United Kingdom, and comparing the model’s outputs to the original master plan. The model proposed a solution based on high density housing exclusively and divided the town into two separate self sufficient clusters. This solution equated to

a 52% reduction in energy consumption over the original plan. However, this was seen as undesirable for potential residents by the town developers, as the solution included low levels of car ownership and high amounts of building homogeneity. The model was rerun with constraints to increase building heterogeneity and improve realism in some aspects, which resulted in a solution closer to the original plan, although with greater amounts of high density housing and clustering of activities. The constrained solution resulted in a 28% reduction in energy consumption over the original plan. The researchers then used Monte Carlo simulation to first test the sensitivity of the model to input parameters and then to analyse energy outputs for variations in input values. They found that increasing the allowable fraction of high density housing decreased total energy consumption and increasing the allowable level of car ownership increased transport energy consumption. The model's results provide some direction for the development of new urban areas, but do not shed light on the ways in which future energy constraints will impact existing urban forms.

### 2.4.5 Transport energy in urban planning

[Saunders, Kuhnimhof, Chlond and da Silva \(2008\)](#) developed an assessment methodology to incorporate transport energy analysis in urban planning. The method estimates the energy consumption required to meet a set of “common activities”: education, work, grocery shopping and recreation. The tool allows the planner to define a future per-person energy intensity within the study area, then iteratively refine future development options such that the planned energy intensity figure is met. The method uses a set of assumed rules for the frequency of activity access and mode selection. A case study implementing the model highlighted the “positive effects of activities being integrated into residential areas” on energy consumption ([Saunders et al., 2008](#), p. 881) . The method combines basic elements of accessibility analysis with energy consumption, and presents planners with a tool for analysing the relative energy impacts of different development patterns.

[Marique and Reiter \(2012\)](#) identified that private transport energy consumption is rarely taken into account during the assessment of new developments, even in so-called “sustainable” or “eco” districts. However, as most of these new developments are located on the urban fringe and distant from city centres, levels of transport energy consumption are likely to be a significant contributor to overall energy consumption in these areas. The authors developed a quantitative method to assess transport energy consumption at the neighbourhood scale in urban areas, based upon and extending

the work of [Boussauw and Witlox \(2009\)](#). The method utilised detailed information available in the Belgian national census, including travel mode for journey to work or school, information on days worked per week, and distance travelled to work or school. Distances between home and public transport services were assessed using Geographical Information Systems (GIS). Frequency of travel for purposes other than work or school were assumed upon the basis of demographic profiles within areas, as this information is not contained within the Belgian census, and distances were computed using GIS. The model was applied to four urban neighbourhoods, each representative of a different sprawled urban pattern in the Walloon region of Belgium. Distances between the central city and the studied areas ranged from six to 29 km, distances from the studied areas to train stations varied from six to 15 km, and the level of service for buses ranged from “very low” to “good”. The model results indicated energy consumption figures for workers ranging from 16 to 29  $\frac{GJ}{year}$  and for students between three and 17  $\frac{GJ}{year}$ . The relative ranking of each area was the same for both workers and students. The results indicated high dependence upon private cars in the Walloon region of Belgium, the importance of distance between home and destination to transport energy consumption, and to a lesser extent the energy contributions of vehicle performance, working from home and public transport by bus.

### 2.4.6 Accessibility

The term *accessibility* describes the ease with which activities can be accessed and incorporates two components: amount and nature of movement, and amount and nature of activities ([Mitchell & Rapkin, 1954](#)). Accessibility is often contrasted with *mobility*, the traditional goal of transport planning, which prioritises ease of movement without considering the purposes of travel ([Chapman & Weir, 2008](#)). Typically, studies involving either assessment technique have been limited to assessments of private vehicle travel ([Iacono, Krizek & El-Geneidy, 2010](#)). Improvements in mobility are often implemented through measures to increase travel speed or reduce congestion for private vehicles, and rarely consider other modes. Private vehicle mobility improvements typically also increase accessibility by private vehicles, although accessibility improvements do not necessarily improve mobility ([Litman, 2003](#)). Accessibility is generally considered to be a more desirable metric but is more difficult to characterise and explain, and as a result in practice it is often under-utilised, measured by inappropriate proxies, and poorly understood ([Geurs & van Wee, 2004](#)).

A number of recent studies have comprehensively analysed accessibility by

public transport or active modes. Frank, Schmid, Sallis, Chapman and Saelens (2005) generated an index for estimating accessibility by walking, commonly termed “walkability”, that takes into account land use mix, intersection connectivity, population density and a measure of retail floor area. The index has been used to understand variations in physical activity linked to health outcomes, such as obesity rates. Kuzmyak, Baber and Savory (2006), as part of a wider accessibility model for the Baltimore Metropolitan Council, developed a walkability assessment that included intersection connectivity, street size and potential destinations, although the analysis included only destinations that were within  $\frac{1}{4}$  mi (400 m) of households. The researchers found that the index introduced a new level of capability into existing land use planning by allowing for direct testing of critical variables underlying efficient community design and transportation need. Manaugh and El-Geneidy (2011) compared the results from the above methods of walkability measurement, as well as two less comprehensive measures, against household travel survey results in Montreal, and found that all the examined walkability indices were highly correlated with walking trips for non-work purposes. McNeil (2011) assessed “bikeability”, based upon existing cycle infrastructure and a system of distance thresholds for various destination types. The method was tested in Portland, Oregon, and showed that destinations in suburban eastern Portland were considerably less bikeable than those in inner Portland. The case study then assessed opportunities for cycle infrastructure improvements and identified unfilled geographic niches for certain destinations. Iacono et al. (2010) developed a comprehensive gravity-based accessibility model for both walking and cycling that calculates accessibility to five destination types. The purpose of the study was to explore issues related to the development of models for assessing accessibility by active modes, and the authors were able to show that many of these issues are surmountable. The Land Use and Public Transport Accessibility Indexing model (LUPTAI), developed by Yigitcanlar, Sipe, Evans and Pitot (2007), assesses access to and from public transport services, as well as the reach and frequency of the service, for a wide range of activities. The results are displayed in comparison with residential density so that possible interventions, increasing public transport accessibility or increasing density, are highlighted and prioritised. Mavoa, Witten, McCreanor and O’Sullivan (2012) combined two measures of public transport access; the accessibility of combined walking and public transport modes, and the service frequency of public transport, into a Public Transit and Walking Accessibility Index (PTWAI) which assessed travel from census units to disaggregate destinations. The researchers assessed Auckland and emphasised that the timing and frequency of many public transport routes provides accessibility for peak hour

commuting but fails to support the trips required for other activities.

Other models calculate accessibility with a consistent methodology across all four modes; walking, cycling, public transport and private vehicle. The commercially available Accession software package<sup>1</sup> was developed in the UK for production of the national Accessibility Statistics (DfT, 2011; Abley & Halden, 2012). The software utilises census units as origins and allows accessibility results to be viewed in a number of different ways. However, accessibility results for each activity are presented as a separate output, and the model has a rigid input structure that makes working with non-UK data difficult (Abley & Halden, 2012). Espada and Luk (2011) developed an accessibility metric for performance monitoring and policy analysis. The metric incorporated transport cost and opportunities at the trip terminus to calculate an accessibility score for walking, cycling, public transport and private vehicle modes. It assesses four trip purposes: Employment, Primary and Secondary education, Tertiary education, and a combined Shopping and Recreation purpose. The results were used to assess three hypothesised effects of accessibility and indicated that areas with higher levels of accessibility coincided with areas of lower travel, higher proportions of non-car travel for work trips and higher property prices. Abley and Halden (2012) developed and implemented the New Zealand Transport Agency (NZTA) accessibility methodology. The model, which runs at the household level, calculates accessibility for seven “consumed” activities and employment over walking, cycling, public transport and private vehicle modes. Unlike other approaches to accessibility metrics, the model cumulates accessibility by each mode, and weights the activity accessibility for relevance to the resident population. It calculates two overall accessibility indices for each household, one for consumed activities and one for employment.

Accessibility analysis combines the influences of land use and transport systems and is a powerful tool for understanding the spatial distribution of transport options available to residents. However, researchers are still unclear as to:

- how much accessibility should be provided, and for whom,
- how the trade-off between accessibility by different modes should be treated, and
- the energy implications of accessibility.

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<sup>1</sup>Further information regarding Accession can be found on the following website: <http://www.citilabs.com/products/accession>

## CHAPTER 3

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# THEORETICAL BACKGROUND

The basic premise of the Minimum Energy Transport Adaptability (META) analysis is not new, however it does represent the first time that this kind of analysis has been applied to urban areas. The method is underpinned by the standard energy engineering approach of building energy modelling. This chapter explains the energy engineering principles of auditing and modelling, how these are used as a basis for the META methodology, and maps a number of key concepts.

The field of energy engineering is concerned with the use, production, distribution, conversion and conservation of energy (Hodgson, 2008). It employs a range of techniques to enable management of energy consumption such that profits and cost savings can be maximised, and environmental goals achieved (Capehart, Turner & Kennedy, 2006). Energy management is often implemented for buildings or industrial facilities. Energy consumption is a function of two factors: fixed characteristics of the system, and patterns of behaviour. For example, the fixed characteristics of the system in a building include the design and materials, location of the building, and climatic factors. Behavioural patterns include the activities performed within the building and the ways in which occupants utilise energy conversion equipment.

### 3.1 Energy auditing

An energy audit is a form of analysis undertaken to understand the uses of energy and identify opportunities for energy cost reductions. The process of an audit for a building or facility is to:

- quantify the energy inputs and costs,



- understand how the energy is used, or possibly wasted, by assessing the energy-consuming activities undertaken, and
- assess levels of service for the building and energy conversion equipment, specifically for the activities being conducted.

An energy audit critically analyses both the fixed characteristics of the system and the patterns of behaviour to identify opportunities for energy cost reductions while maintaining level of service. These opportunities fall into two general categories:

**Energy Conservation Opportunities:** changes to the fixed characteristics of the system to reduce energy costs. For example, changing a household lighting system from incandescent to compact fluorescent will reduce costs through reduced energy consumption and increased equipment lifespan without affecting the intensity of light for conducting activities.

**Energy Management Opportunities:** implementation of plans or devices to reduce energy consumption by modifying patterns of behaviour. For example, controlling hallway lighting through a movement sensor or timed switch rather than a manual switch.

## 3.2 Energy modelling

Building energy modelling is a simulation tool which calculates the thermal loads and energy use of residential and commercial buildings (Ryan & Sanquist, 2012). Growing energy concerns, particularly regarding price and environmental impact, have increased the use of energy modelling for the design of “green buildings”, and many building energy models are currently used around the world. The models are typically applied in the design of new buildings, and in the renovation of existing buildings, to predict energy usage levels. Energy consumption factors described above form the primary inputs of building energy models (Swan & Ugursal, 2009; O’Neill et al., 2011):

**Fixed characteristics:** building geometry, materials, location, orientation, climatic conditions and heating, ventilation and air conditioning system.

**Patterns of behaviour:** occupancy profile, activities undertaken, and the energy consuming appliances used for activities.

The fixed characteristics of a building are known, while behaviour patterns are synthesised from a series of assumptions related to the building purpose or surveyed



information. Holding one of the factors constant while altering the other will change the total building energy requirement; for example, the energy consumption would differ if the same building were used for commercial purposes rather than residential purposes.

The META model applies an analogous building energy modelling analysis to the urban form, assuming that behaviour operates in a transport energy adapted state, to estimate the minimum possible energy consumption. In terms of urban areas the fixed characteristics of the system are land use patterns and transport networks, while patterns of behaviour are a combination of activity frequency and the ability to use various modes dependent upon the resident demography. Land use patterns and transport networks are knowns, defined by the locations of origins and facilities, while behavioural patterns are assumed or derived from surveys. In combination this information defines where, and how often, the specific population needs to travel, and how able they are to use modes, which produces the minimum energy consumption requirement.



## CHAPTER 4

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# METHODOLOGICAL REVIEW

The META method primarily builds upon approaches of accessibility analysis and travel activity modelling, and the output minimum energy value is a form of accessibility measure in which travel activity requirements constitute weighting factors. The technical details of these approaches are reviewed and discussed in this chapter and relevant terms are defined. Furthermore, relevant sources of modal energy intensity values are outlined and reviewed.

### 4.1 Accessibility

The relation of accessibility studies to energy resilience is discussed in chapter 2. This section reviews specific details of accessibility modelling. Handy and Niemeier (1997, p. 1175) state that “[a]ccessibility is determined by the spatial distribution of potential destinations, the ease of reaching each destination, and the magnitude, quality, and character of the activities found there”. There are two distinct, but related, approaches for accessibility measurement: *gravity based*<sup>1</sup> and *utility based* (Koenig, 1980; Handy & Niemeier, 1997; Dong, Ben-Akiva, Bowman & Walker, 2006). Derived from the denominator of the gravity model for trip distribution, *gravity based measures* calculate accessibility by weighting available opportunities relative to the the impedance of reaching them. Impedance can take the form of distance, time or some function of financial travel costs. *Utility based measures* build upon the theories of behaviour and random utility. These measures assume that people associate utility with each

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<sup>1</sup>This definition of *gravity based measures* of accessibility also encompasses measures utilising a stepwise impedance function, often termed *isochrone* or *cumulative opportunities* measures.

alternative combination of destination and mode available to them. However, utility is not known with certainty by the analyst, and is therefore treated as a random variable with two components: the observable attributes of alternatives that are assumed to impact the decision, termed the systematic utility, and the unobservable portion of utility, termed the disturbance. Various studies have used different model forms predominantly based around the generalised extreme value (GEV) model, including multinomial logit (MNL) and nested logit (NL) models. The advantage of utility based accessibility measures is that they can be tailored for specific categories of individuals and capture the compromise between various modes. The META method characterises the spatial distribution of limits to transport energy adaptation within urban areas, and consequently draws upon theories of gravity based accessibility measures.

Accessibility can be determined either for origins or destinations, however the META method is concerned only with origin accessibility. A gravity based measure of accessibility for an origin simulates a question such as *how many shopping opportunities could be reached from a given household*, while a comparable example for destination accessibility would be *how many people could access a given shop*. Expressed mathematically, the gravity based accessibility of an origin point ( $i$ ) to destination opportunities ( $j \dots n$ ) is commonly defined by the equation (Handy & Niemeier, 1997; Geurs & van Wee, 2004):

$$A_i = \sum_{j=1}^n O(j, o_j) f(c_{ij})$$

where:

$O()$  is an *opportunity weighting function* (saturation function) such that there is a diminishing return upon reaching additional destinations;

$o_j$  is a measure of opportunities (or benefits) at each potential destination ( $j$ );

$f()$  represents an *impedance function* of some form, defined such that accessibility decreases as cost increases; and

$c_{ij}$  specifies the “cost” of travel between the origin ( $i$ ) and each destination ( $j$ ). This cost is a generalised impedance, and in practice can be distance, time or some calculated or estimated function of financial travel costs.

The equation calculates the total accessibility of the origin. Destinations or origins in the equation can also be represented as areas; for example, the number of employed persons in each suburb could be an areal measure of opportunities for employment.

The opportunity weighting function represents the diminishing benefit of reaching additional destinations, for example, reaching one supermarket provides significant benefit, but reaching a 12<sup>th</sup> supermarket provides little more benefit than was gained cumulatively upon reaching the 11<sup>th</sup>. Depending upon its formulation the opportunity weighting function can also include some measure of the opportunities available at the destination, such as floor area or employment opportunities. Equations often used for the opportunity weighting function include (Iacono et al., 2010; Espada & Luk, 2011; Abley & Halden, 2012):

- raw opportunities (no weighting)

$$O_j = o_j$$

- arithmetic weighting

$$O_j = \frac{1}{j} o_j$$

- exponential decay weighting

$$O_j = \frac{1}{e^{j-1}} o_j$$

A comparison of these three equations is given in figure 4.1.

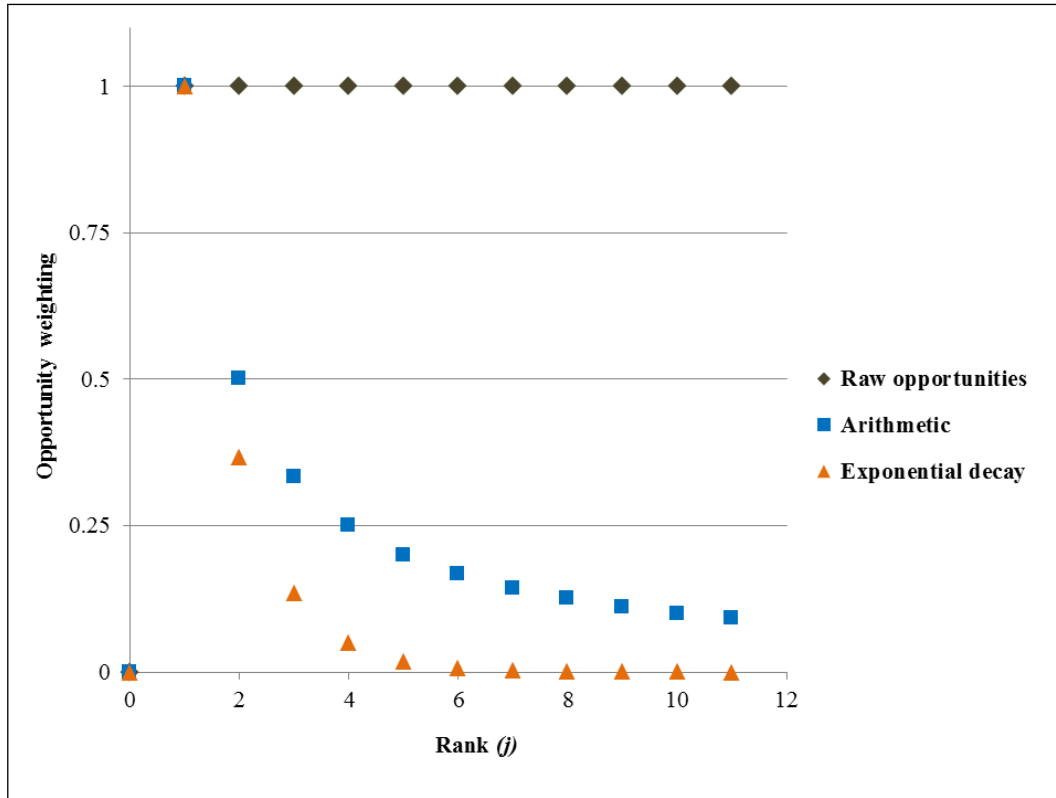
The impedance function represents the dampening effect that increasing time, distance or financial costs, exert on travel, and is designed and calibrated to fit surveyed travel data. Various impedance functions have been used by different studies including stepwise, power and Gaussian functions, but the negative exponential function is the most often used and also has the closest ties to travel behaviour theory (Handy & Niemeier, 1997; Geurs & van Wee, 2004). The negative exponential function is described by the equation

$$f(c_{ij}) = e^{-\lambda c_{ij}}$$

where larger  $\lambda$  values relate to higher rates of decay. However, recent studies have shown that the weighted logistic function provides a better fit to survey data (De Vries, Nijkamp & Rietveld, 2009; Abley & Halden, 2012). The weighted logistic function is described by the equation

$$f(c_{ij}) = \frac{1 + e^{-\alpha\beta}}{1 + e^{\beta(c_{ij}-\alpha)}}$$

where  $\alpha$  defines the  $c_{ij}$  value of maximum change and  $\beta$  is a shape fitting parameter. A comparison of the stepwise, negative exponential and weighted logistic functions is shown in figure 4.2 with the stepwise threshold  $c_{ij} = 30$ , exponential function  $\lambda = 0.037$ ,

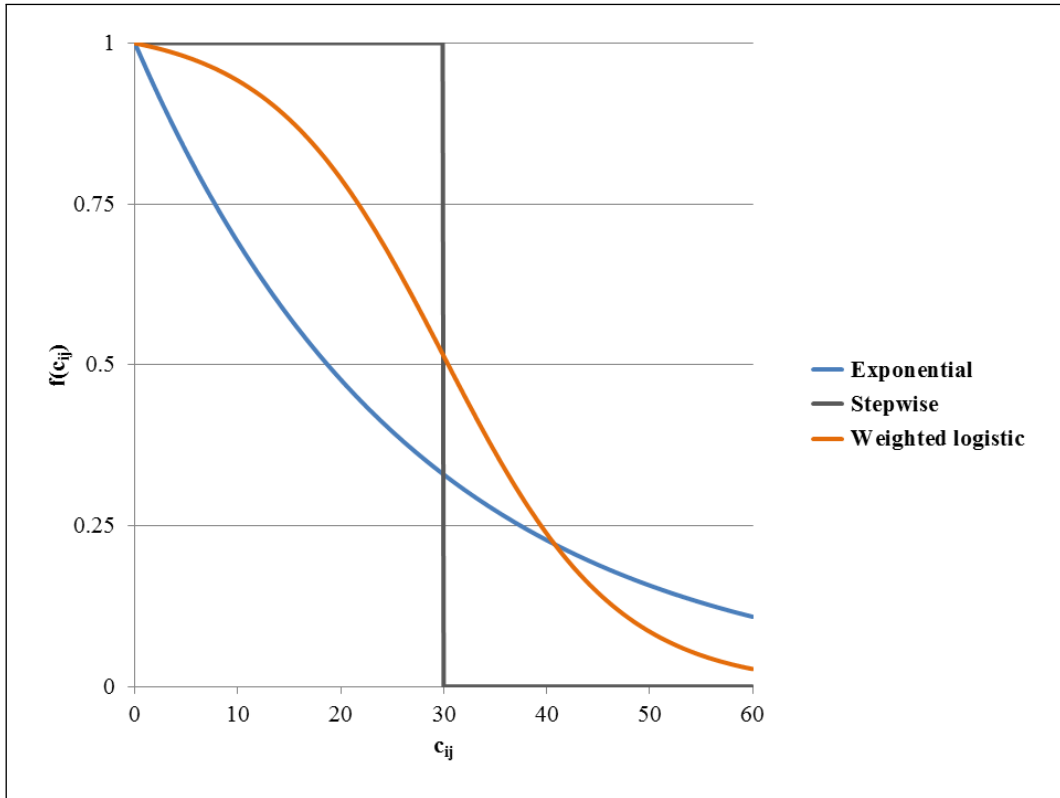


**Figure 4.1:** Comparison of opportunity weighting functions commonly used in accessibility modelling

and logistic function  $\alpha = 30$  and  $\beta = 0.12$ .

Conventional transportation planning is often focused on improving mobility by private vehicle; consequently, the majority of existing accessibility studies measure only for the private vehicle (Iacono et al., 2010). Furthermore, many studies focus solely on accessibility to employment as it links with other important aspects of urban structure, such as choice of residential location, and also to outcomes hypothesized to be related to urban structure, such as social exclusion (Iacono et al., 2010). However, the basic accessibility equation may be applied to any activity and mode if relevant functions and input data are known (Iacono et al., 2010; Abley & Halden, 2012). Determining impedance functions for active modes can be difficult, as the majority of travel surveys collecting impedance data are designed to inform models of private vehicle travel (Kuzmyak, 2012). As fewer trips are made by active modes there can be issues in collecting a sufficient number of samples from which to draw inferences, particularly when the data is further stratified for analysis by activity (Iacono et al., 2010).

Accessibility results can be presented in a variety of ways. Most studies utilise



**Figure 4.2:** Comparison of impedance functions commonly used in accessibility modelling

some form of indicator, although this may depend upon the impedance function used within the model (Abley & Halden, 2012). There are two general types of accessibility indicator (Abley & Halden, 2012):

- **Threshold** indicators, also called isochrone or cumulative opportunity indicators, are calculated where the stepwise function is used for impedance. Threshold indicators are usually presented in the form of a value answering a question for an origin or area, for example the United Kingdom Accessibility Statistics include results such as “the number of jobs located within 20 minutes of a Local [Government] Area” (DfT, 2011, p. 3). However they can be presented spatially, showing the distribution of areas within and outside of the threshold.
- **Continuous** indicators are calculated using continuous functions such as the negative exponential or weighted logistic for impedance. Continuous indicator results are typically presented spatially to show the detailed variations in accessibility.

Furthermore, indicators can be combined to form *composite indicators*. For example, the NZTA Accessibility Methodology indicator weights and combines continuous

accessibility indicators for all modes and activities to produce a single overall value representing the origin accessibility of households (Abley & Halden, 2012). Threshold indicators can similarly be weighted and combined, producing a continuous composite indicator that may be viewed spatially.

## 4.2 Travel activity modelling

The application of activity based approaches is increasing within the field of transportation research, and there is a growing body of literature detailing their use in practice (Algers, Eliasson & Mattsson, 2005; Iacono, Levinson & El-Geneidy, 2008). Activity models are definitions of personal- or household-level patterns of activity. For example, a child will regularly attend school and a working age adult will engage in employment with some frequency. Activity models detail the periodic trips or tours that are undertaken by a person of a certain age or income, or a household of a defined status or composition. The advantage of activity based models over traditional transport modelling approaches is their ability to account for behaviour changes, including responses to travel demand management (TDM) policies. The use of activity-based analysis is already widespread in time use studies and travel surveys; for example, the New Zealand, United Kingdom and United States National Household Travel Surveys all collect trip data in terms of the activity purpose of the trip (Federal Highway Administration (FHWA), 2009; DfT, 2010; Milne, Rendall & Abley, 2011).

Much of the academic literature regarding travel activity modelling attempts to understand the influence of land uses upon the generation of activity patterns or time allocation to activities (Lee, Washington & Frank, 2009). For example, Pas (1988) developed a methodology for the analysis of multiday travel activity patterns. The approach characterised these as sets of daily travel activity pattern types for determining general weekly activity patterns and examining the relationships between activity patterns and hypothesised determinants. Despite small sample sizes, the study found that general classes of travel activity behaviour relate to socio-demographic characteristics. However, travel activity variations between age groups were not analysed. Lee et al. (2009) examined the activity durations for out-of-home subsistence, maintenance, and discretionary activities based upon travel survey data. The researchers also examined travel *tours*, which are combinations of activities usually starting from and returning to the same location, and the differences in time allocated for weekday and weekend travel. The study found significant relationships between residential urban form and time spent on all activities. Interestingly, the researchers also found that time



lost to congestion in travelling to subsistence activities resulted in lesser allocation of time to discretionary activities, including health and quality of life related activities. Other studies have used activity modelling in a diverse range of applications, such as modelling transport activity impacts on air quality or health (e.g., [Badland et al., 2009](#); [Beckx et al., 2009](#)).

Further studies focus on using activity data for travel modelling or understanding the spatial implications of travel to activities. However, many of these studies use travel activity modelling not only to understand the number and nature of trips made, but also the times at which travel to various activities occurs ([Bowman & Ben-Akiva, 2001](#)).

[Stopher et al. \(1996\)](#) proposed the Simulation Model for Activities, Resources and Travel (SMART), which would integrate household activities, land use patterns, traffic flows and regional demographics, as a replacement for traditional transport models. The model would be developed within a GIS environment, and produce traffic volumes on streets and land use intensity patterns as well as typical travel outputs. The researchers generated, for five different generalised household types, an estimation of the requirements for Work, Work-Related, School, Medical and Sleep activities.

[Wang and Cheng \(2001\)](#) developed a concept for a spatio-temporal data model to support activity based transport demand modelling in a GIS environment. The model would represent activity patterns as a sequence of staying at or travelling between activity locations, allowing analysis by location, time or persons. A prototype was implemented in a GIS environment and tested with a case study in Hong Kong.

[Bowman and Ben-Akiva \(2001\)](#) developed an activity based transport model in Portland, Oregon, utilising travel survey data. The activity model is stratified into multiple levels, the highest of which determines the activities which will be carried out during a day, while sub-levels determine the characteristics of tours and sub-tours, such as timing and mode. The model outputs are similar to traditional transport modelling outputs: origin-destination (OD) matrices by mode, purpose, time of day and income class. The model has since been applied in San Francisco, New York City, Columbus and Atlanta ([Algers et al., 2005](#)).

A rule based approach to activity modelling was developed by [Arentze and Timmermans \(2004\)](#), called the Albatross model, which balances the requirement of households to engage in activities with constraints presented by the physical environment and institutions. It predicts for each adult individual in a household the daily probability of each combination of activity, location, travel party and mode of transport which are dependent on activity agenda, available modes and land use patterns.

Saunders et al. (2008), in their model to incorporate transport energy into urban planning, utilized age cohorts to define common activities that are performed at a homogeneous rate within the cohort. For example, the study estimated that pre-school through to secondary school education is an activity attended five times per week by children aged 3 to 17, while people 18 and over engage in shopping twice per week; although, these numbers were not derived from survey results. This study focused on the generalised energy implications of travel, rather than modelling traffic flows, and thus did not consider time of travel or activity scheduling.

One modelling approach, the activity-based accessibility (ABA) measure, developed by Dong et al. (2006), combines accessibility with activity modelling. The ABA is a utility based measure of accessibility that considers travel to all activities, incorporates trip chaining, the full set of activities pursued in a day and the scheduling of activities. The ABA model utilises the activity system described by Bowman and Ben-Akiva (2001) which consists of an activity pattern specifying the daily set of activities undertaken by an individual, and an activity schedule, which defines the sequence and timing of tours, location of activities, and travel modes. The ABA measure is defined as “the expected value of an individual’s maximum utility among the available activity schedules, given his or her residential location” (Dong et al., 2006, p. 167). The advantage of this approach over traditional utility based measures is that all trip purposes are modelled concurrently, and trip chaining and scheduling can be taken into account.

### 4.3 Summary

The META characterisation is based upon gravity measures of accessibility. It uses an estimation of mode ability for the specific resident demography to determine the stepwise impedance function for each mode, and surveyed patterns of activity frequency for the specific resident demography to determine the frequency of travel to each activity.

### 4.4 Modal energy intensity values

Energy intensity values for car and bus transport derived from a variety of sources are summarised in table 4.1. Newman and Kenworthy (1999) performed an analysis of the transport energy systems of 37 cities around the world, their results indicate that European cities have lower energy intensity for car and bus transport than Australian

cities, and both have lower intensities than American cities. The Transport Energy Data Book values presented by [Davis, Diegel and Boundy \(2011\)](#) are based at the national level in America, and are available for a variety of years. The variation between these figures and the values of [Newman and Kenworthy \(1999\)](#) is negligible for buses, but significant for cars. This indicates that car travel in American cities is more energy intensive than national car travel, most likely due to the effects of congestion and lower occupancy. As bus services are only present in cities there is little variation between the two. The values also show decreasing energy intensity of American car travel between 1990 and 2009, in spite of a three percent decrease in occupancy over this period, indicating an increase in vehicle efficiency or decrease in losses due to congestion ([Davis et al., 2011](#)). Conversely, the energy intensity of bus travel has increased, indicating decreased occupancy. The New Zealand energy intensity figures provided by the [Centre for Advanced Engineering \(CAE\) \(1996\)](#) are surprisingly low, both presenting lower intensities than those for the average European city. However, [CAE \(1996, p. 474\)](#) quote their sources as “[u]npublished estimates, information and opinion based on a variety of information sources, and provided to the [authors]”, which is unlikely to be as robust as the measurement techniques used in the other studies. It appears that the Ministry of Transport (MoT) once estimated New Zealand values of energy use per passenger-kilometre, but have elected to discontinue reporting this metric ([MoT, 2009](#)). None of these MoT estimates could be located. The most representative values for New Zealand cities are the 1990 figures presented by [Newman and Kenworthy \(1999\)](#) for Australian cities. It is noted that these values are likely to overestimate the overall energy consumption for private vehicles and underestimate that for public transport, assuming that American trends of energy intensity between 1990 and 2009 are typical.

Table 4.1: Energy intensity values and source

Location ( <i>n</i> )	Metric	Energy intensity ( $\frac{MJ}{p-km}$ )		Data year	Source
		Car	Bus		
Australian cities ( <i>5</i> )	Minimum	2.80	1.11		
	Maximum	3.43	2.40		
	Average	3.02	1.68		
American cities ( <i>10</i> )	Minimum	2.91	1.83		
	Maximum	4.20	2.99	1990	(Newman & Kenworthy, 1999)
	Average	3.51	2.45		
European cities ( <i>11</i> )	Minimum	1.89	0.69		
	Maximum	3.10	1.89		
	Average	2.62	1.32		
New Zealand ( <i>urban</i> )	Average	2.27	1.28	1994	(CAE, 1996)
American ( <i>national</i> )	Average	2.53	2.49	1990	(Davis et al., 2011)
		2.32	2.78	2009	

## CHAPTER 5

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# METHOD

This thesis presents an approach for characterising the spatial distribution of limits to transport energy adaptation within urban areas, termed the Minimum Energy Transport Adaptability (META) methodology. The method estimates the minimum transport energy theoretically required by households to meet their current activity requirements. Chapter 2 reviewed the fields of Urban, Land Use and Transport Planning which influence transport energy adaptability, but currently possess no tools for understanding it. The engineering approach of energy auditing which underpins the META analysis was reviewed in chapter 3. Specific modelling approaches, including accessibility and activity modelling, that the META analysis expands upon, were reviewed in chapter 4. This chapter describes the technical approach, data requirements and the methodological algorithm of the META analysis.

### 5.1 META method approach

Transport energy supply pressures will force households to undertake adaptive responses, reducing energy consumption from that observed in unconstrained situations. However, the extent of energy adaptations possible for a household is limited by land use patterns, transportation systems, and activity requirements and physical abilities of residents. There is consequently a lower limit on transport energy consumption, termed the *minimum transport energy consumption*. It is the household transport energy consumption if all viable short term adaptations have been enacted. The potential short term adaptations are (Krumdieck et al., 2010):

1. combining travel to multiple activities into a single trip chain;

2. using a more efficient vehicle or shifting to a less energy intensive mode; and
3. selecting activity destinations that require less travel, including participating without travel.

The META method estimates the household minimum transport energy consumption given the specific land use patterns, transport networks and population demography of an urban area. The method currently does not assess adaptive energy reductions as a result of increases in trip chaining or vehicle occupancy. The estimation applies the following principles, synthesising a situation in which viable short term mode and activity travel adaptations have been adopted:

- Activities:**
1. The closest facility for any non-employment activity is a viable destination for that activity.
  2. A number of possible employment facilities must be available, to account for labour specialisation.
  3. The current frequency of travel to activities is a necessity.

**Mode:** The lowest-energy mode within the ability of the residents is utilised for travel to each activity. The following threshold hierarchy is applied:

1. if the trip is within the resident's walking ability, it is walked;
2. if the trip is not walkable, but is within the residents' cycling ability, it is cycled;
3. if the trip is neither walkable nor cycleable, but routes are available and the trip would be within the public transport ability of the residents, the trip is made by public transport;
4. if neither active modes nor public transport are viable for the trip, it is made by private vehicle.

The META method for characterising the minimum energy consumption is outlined in figure 5.1. The META analysis is an activity-weighted composite indicator of accessibility, where mode ability defines the threshold of the stepwise impedance function for each mode. Coupled with the premise that the closest activity facility is a viable destination for that activity, the total travel requirement by each mode in reaching all activities can be calculated. The META minimum energy consumption is the product of energy intensity and travel requirement for energy consuming modes. Activity frequency and mode ability are termed *constant inputs*, and are derived

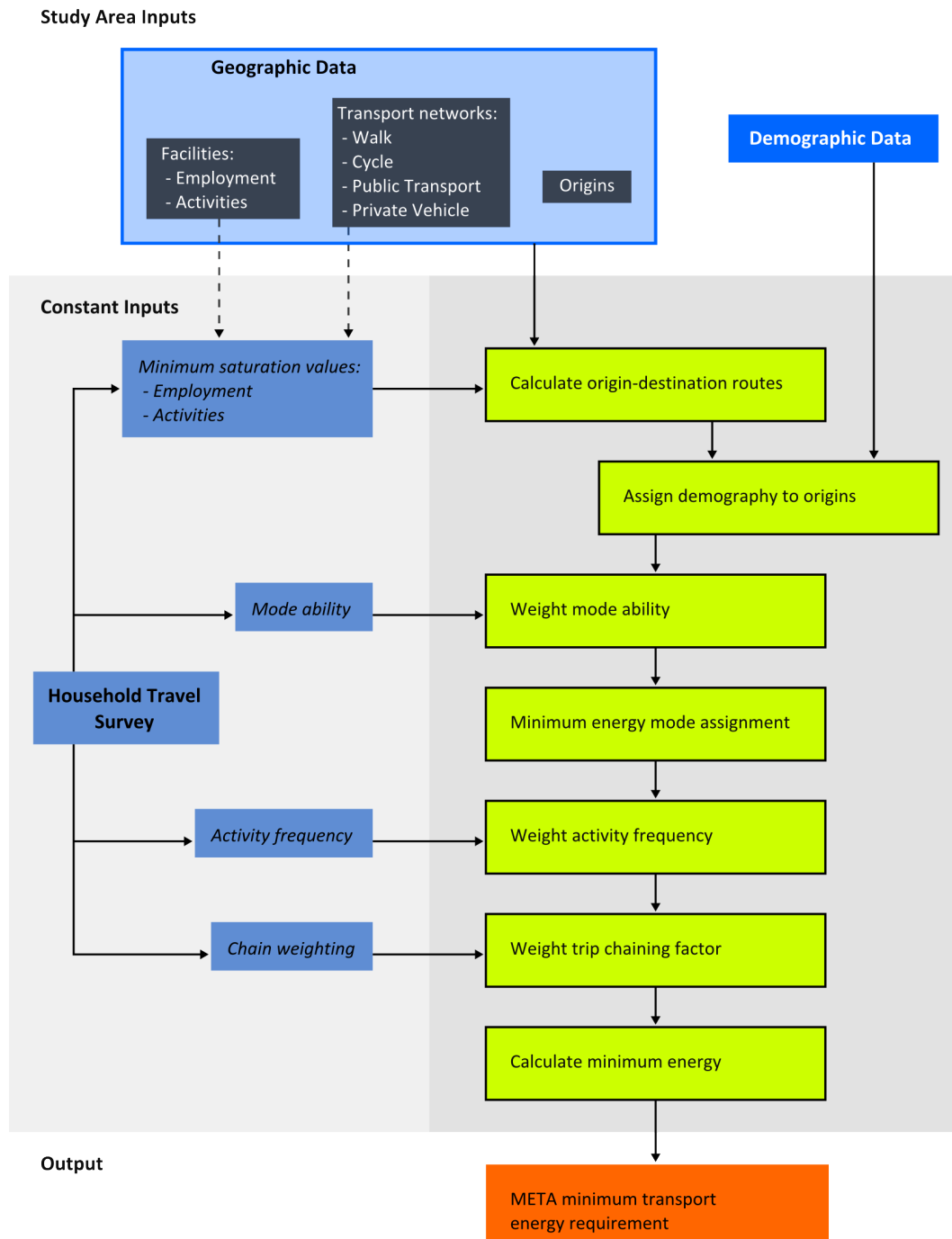
nationally from household travel survey data. Origins, destinations and transport networks are represented in GIS for each study area, and are collectively termed *study area inputs*.

An idealised urban form with a number of houses, one of which is selected, and four types of activity facility; primary school, post office, park and shop, is shown in figure 5.2. The red line shows the quickest route by private vehicle between the selected residence and the closest post office, while the blue line shows the quickest route to the same destination by active mode, either walking or cycling. For simplicity, public transport is not shown in this example. Similar routes can be calculated for each activity. Travel from the household to a destination, termed a *trip* and made by a *mode*, allows the residents to participate in activities at the destination. The META minimum energy value for a household and set of destinations is calculated using the minimum energy mode assignment threshold hierarchy described above. Destinations within the walking ability of the residents are accessed by walking. Of the remaining destinations, those that are within the cycling ability of the residents are cycled. If the residents are unable to access a destination by active modes, but public transport provides a route and allows them to reach the destination within the limit of their public transport ability, including walking at both ends of the trip, the destination is accessed by public transport. If the trip cannot be made by active modes or public transport it is assumed to be made by private vehicle. The distance from the residence to each of the destinations multiplied by the annual frequency of participation in the corresponding activity, which includes current levels of trip chaining, and the modal energy per unit distance produces the META minimum energy consumption. The META characterisation is not a measure of behaviour or predictor of future travel, but a geographical measure of the potential that a household possesses to adapt transport energy consumption. Households with a high META minimum energy have fewer adaptive options than households that possess the ability to reach all of their activity destinations by active modes.

The theoretical META method applies the following assumptions:

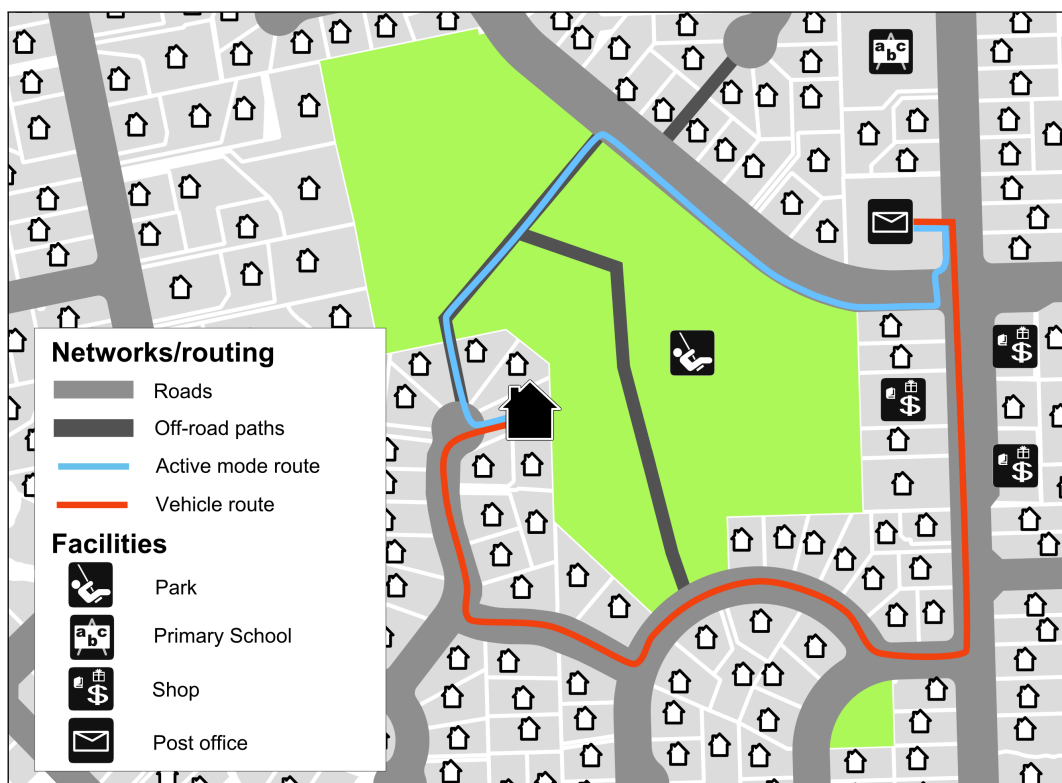
1. Age is the key determinant of:

- the particular activities carried out by an individual and the frequency of their participation in them,
- the ability of a person to travel by different modes, and
- the extent to which a person currently engages in trip chaining.



**Figure 5.1:** Outline of the META method





**Figure 5.2:** Example urban form: networks, destinations and quickest route to the closest post office by active modes and vehicle

2. The ability of a person to use a given mode is dependent upon the travel time by that mode.
3. Modes specified by the minimum energy hierarchy are viable for the trip. This neglects the effects of weather, loads, passengers, travel perceptions, accompanying minors and emergency travel.
4. Trips to all activities are home-based, meaning they originate at the home and return once complete.
5. The adaptive response of vehicle occupancy increases is neglected; hence, modal energy intensity values for public transport and private vehicles, defined in terms of Megajoules consumed per passenger-kilometre, are constants.
6. The adaptive response of increasing trip chaining is neglected.

The model represents current levels of trip chaining in a non-spatial manner, effectively scaling the activity frequency by the current amount of trip chaining undertaken. Due to limitations in data availability and travel survey design characteristics, and to simplify model development, the implementation of the META method applies the following assumptions:

1. Age-dependent mode ability can be defined as the 75<sup>th</sup> percentile value of surveyed travel time for each mode, by people of the specified age group.
2. Minimum saturation values can be defined as the 25<sup>th</sup> percentile saturation value for each activity within survey activity classifications.
3. Each facility for an activity, up to the minimum saturation value for the activity, attracts an equal share of the trips to that activity.
4. Current levels of trip chaining can be calculated as a demographic property and applied to household travel patterns.
5. Demography can be assigned to households in a given census area as the average age and number of residents within the census area.

These implementation assumptions are described in further detail as they are applied throughout the remainder of this chapter, and all assumptions are reviewed and discussed in chapter 7.

## 5.2 Study area inputs

The method utilises a range of geographic data at the study area level. This data defines demographic properties, origin and facility locations, and transport network locations and properties. The data can represent study areas as they exist at present or can be modified such that the model could test proposed development scenarios. Furthermore, it is possible to synthesise data and test suggested new or hypothetical developments.

Geographic information is stored on computers in the form of GIS data, which is a linking of information with a spatial location. Points, lines and polygon shapes, termed features, are stored as vectors represented within GIS databases as points, or ordered combinations of points, on a Cartesian plane or spheroidal surface. These are projected onto a Cartesian plane, such as a computer screen or sheet of paper, for viewing. Attribute information, consisting of at least a unique identifier, is linked to every feature. A wide variety of information may be stored as attribute information, such as the address associated with a property, the opening hours of a shop or the number of residents within a city. Calculations can be performed on attributes to modify their values or generate new attributes. This section briefly describes each set of geographic data used, potential sources and data availability or quality issues. The data sources actually used in the case studies are described in detail in chapter 6.

### 5.2.1 Demographic data

The method required the age profile and number of residents for every household within study areas. This information is not available at such a fine level of detail, but it can be approximated from census data. The census is a periodic national count of people and dwellings, which many countries conduct once every five or 10 years. Census information, which is distributed in a non-spatial database, was joined with the relevant geospatial census area boundary data for use in the model. For some applications it is desirable to represent boundaries as points, in which case the centroid of the polygon is used to represent the polygon. The model assumes that each household within a study area possesses the average number of residents of the average age contained within the area.

NEW ZEALAND: The census is conducted by the government body Statistics New Zealand. Results of the national census are summarised at various levels, the smallest of which is the collection area called a *Meshblock*, which has no

particular size or population definition. A variable number of Meshblocks are aggregated into *Area Units*, which typically have a population of 3,000 to 5,000 people. The results are also available at further levels of aggregation including Ward area, Territorial Authority, Regional Council and at the national level. To protect privacy the data is confidentialised if three or fewer people can be identified within the results for a particular area; as a result, Meshblock level data can often not be used. Age profile information within the census is grouped into five year bins for all ages between zero and 65, and a final category contains all respondents over the age of 65 ([Statistics New Zealand, 2012](#)). Census collection boundaries are represented as polygon areas, and are available at the same levels as those to which the data is summarised: Meshblock, Area Unit, Ward area, Territorial Authority and Regional Council. These boundaries can be joined to the data by area identifiers.

### 5.2.2 Origins

Population residences within the study area, henceforth in this analysis termed *origins*, were represented within the model as GIS points. This data is potentially available from a range of sources, including local and regional authorities and land information agencies. It is also possible, if necessary, to synthesise origins from either land package or census data. The origins require no attribute information, although census demography data was later attached to each origin depending upon its spatial location.

### 5.2.3 Activity facilities

Activity facilities are also represented as GIS points. This data is potentially available from a range of sources, including local or regional authorities, land information agencies, and, increasingly, community contributed sources. Ideally, every personal travel destination would be represented within the data. However, the accuracy, density and quality of the data is often limited; for example, authorities may only have zoning-level data or the sites of large retail facilities instead of coverage to the required level of detail. For use in the model, facilities were classified in accordance with the activity classification scheme of the travel survey used to develop the Constant Inputs described in section 5.3. Aside from the activity classification of each facility, no attribute data was required.

NEW ZEALAND: The Zenbu collaboratively edited directory of businesses and places, <http://www.zenbu.co.nz>, which allows people and organisations to record places of interest, represents the most comprehensive source of facility data available. Destination points were manually classified in accordance with the New Zealand Household Travel Survey (NZHTS). Issues regarding the use of this data are discussed in chapter 7.

#### 5.2.4 Employment facilities

Employment facilities are represented by the number of employment opportunities per census area, available from government records. This data was joined to the relevant census area centroids, represented within GIS as point features, to produce a spatial pattern. The only attribute information required was the number of employees within each area.

NEW ZEALAND: Employment information is available from the government body Statistics New Zealand in a non-spatial database summarised at each of the census collection levels. The smallest possible census data collection unit was used, in New Zealand this is the census Meshblock.

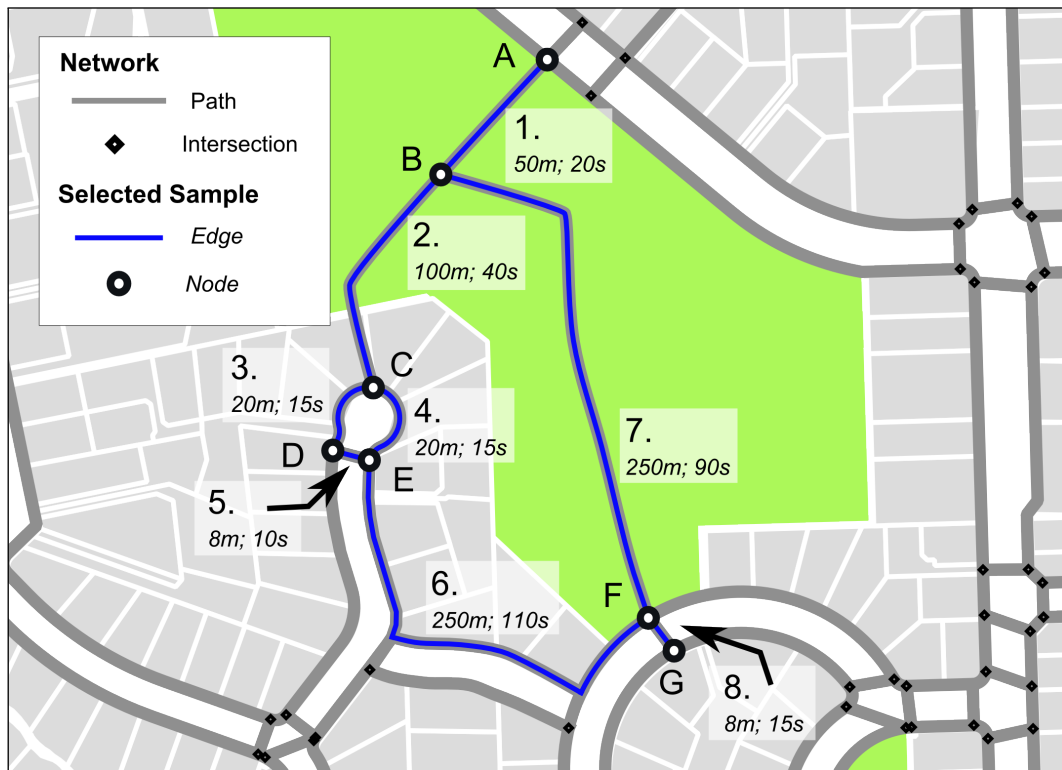
#### 5.2.5 Transport networks

Transport networks are represented as connected collections of line features. Attributes vary by mode, but the travel time and distance along each link is a requirement for all modes. The distance along each link is a geometric property, but can be explicitly stored as an attribute. As it is a derived characteristic, the level of detail included in the calculation of travel times can vary. For example, although the distance will remain constant, the travel time by private vehicle on a road will vary depending upon the time of day, due to the effects of congestion or variable signal plans. For walking, cycling and private vehicle the simplest calculation assumes a constant travel speed for each mode, without accounting for intersection delays. The travel time calculation for walking can be improved by including delays incurred when crossing streets, both at and between intersections, and cycling and private vehicle can be enhanced by including intersection delays. Private vehicle travel time can further be improved if real traffic flow speeds, derived from transport planning models, are included. Public transport is the most detailed network, as it includes service frequencies, stops, and complex

connections both within the network and to the walking network at either end of the journey. It is possible to include any type of public transport service, or combination of services, within the data.

The networks were converted to graph representation for use within the model. Graph representation removes the network from a spatial environment, instead representing it as a series of nodes connected by edges quantified only as impedances. The impedance can take any form, but for transport networks it is usually distance, travel time or monetary cost. An example walking network, part of which has been selected with nodes identified by letters, edges identified by numerals and edge impedance attributes specified, is shown in figure 5.3. The graph representation of the selected network portion is presented in table 5.1 as a triangular matrix as, for this simple example, impedance is assumed constant regardless of travel direction.

NEW ZEALAND: Data on transport networks is typically held by government authorities, such as councils or land information agencies. In New Zealand this data is often freely available, although it tends to be infrequently updated and of poor quality. Higher quality data is typically available within transport consultancies where public data has been corrected, updated and had further detail added to it.



**Figure 5.3:** Walking network example with sample selected for graph representation

**Table 5.1:** Matrix of example transport network in graph representation

Link traversal time (seconds)							
	A	B	C	D	E	F	G
A							
B	20						
C	-	40					
D	-	-	15				
E	-	-	15	10			
F	-	90	-	-	110		
G	-	-	-	-	-	15	

### 5.3 Constant inputs

The constant inputs form a locationally independent specification of mode abilities, activity frequencies and the number of destinations required for an activity which, when applied to the geography and demography of a specific urban form, characterises the META minimum energy consumption. There are three constant inputs required by the model that are derived from household travel survey results: mode ability, activity frequency and trip chaining. A fourth constant input, minimum saturation, is derived from household travel survey results in conjunction with destination data.

Household travel surveys are conducted in many countries for the purpose of collecting statistical information relating to transport and for use in the calibration of transport models. Surveys are typically conducted at either the national, regional or city scale and focus on measuring travel characteristics at the personal or household level. These surveys are typically based around activities undertaken by the respondents. Some examples of the types of activities assessed within various international surveys are shown in tables 5.2 and 5.4.

NEW ZEALAND: The NZHTS is an ongoing national-level survey used for assessing travel trends and changes over time (Milne et al., 2011). The NZHTS collects information on every trip leg made by the respondents over a period of two days, as well as personal and household information.<sup>1</sup>Data concerning alcohol consumption and accidents is also collected, but was not used in this research. The dataset is provided by the New Zealand Transport Agency (NZTA) in the form of a Comma Separated Variable (CSV) database for each level of classification: Trips, Persons and Households. These are linked by a unique ID field for each household, and persons are further identified by a number within the household. Trip legs are defined as a one way course of travel, from an origin to a destination, with a single main purpose: the activity conducted at the destination. For example, a person travelling from home to their primary place of employment would be recorded as a trip leg with the purpose of *Work - Main Job*. There are 16 activity classifications used within the survey, defined in table 5.2. Some classifications are not relevant for this research, as the method uses only activity purposes that can be applied to fixed physical destinations. The mappings between the NZHTS definitions and META definitions are outlined in table 5.3; NZHTS categories unused in the META model are listed as *n/a*, while mappings where multiple categories are



converted to one, and vice versa, are highlighted. The survey records a number of other attributes for each trip leg including the mode of transport, departure and arrival times, the number of passengers in the vehicle if the respondent is driving a vehicle, trip leg origin activity and the spatial location of the origin and destination. As the sample selection method of the survey is not strictly random, the dataset includes weighting factors for all trips, persons and households. These weights account for the probability of household selection, person selection and non-response, and must be used in the calculation of all estimates from the dataset (Milne et al., 2011).

The META method has only been applied at the city level. Consequently, all the constant inputs are based upon travel survey responses from residents of what Statistics New Zealand terms Main Urban Areas; these are urban areas with a population of over 30,000 people (Milne et al., 2011).

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<sup>1</sup>Detailed information regarding the NZHTS is available from the Ministry of Transport website: <http://www.transport.govt.nz/research/TravelSurvey/>

**Table 5.2:** NZHTS trip activity classifications and descriptions

NZHTS classification	Description
Home	Trips to the home
Work: Main	Trips to a workplace with fixed location; job with greatest number of hours worked
Work: Other	Trips to a workplace with fixed location
Work: Employers Business	Work trips to a non-fixed location or work-related travel
Education	Travel for the purpose of education
Shopping	Trips to locations where goods can be purchased or hired
Social welfare	Trips to government agencies involved in welfare
Personal business	Travel to conduct personal business where no goods are involved
Medical/dental	Trips to serve medical or dental needs
Social visits	Trips for the purpose of engaging in social activities
Recreational	Trips for sporting activities or to engage in exercise/sport
Change mode	Trips for switching to another mode of transport
Accompany someone	Making a trip to accompany another person
Left country	Trip where the respondent left the country
Other	Other purpose
Overnight lodgings	Purpose was overnight accommodation

**Table 5.3:** NZHTS activity classifications, list of META activity classifications and mappings between activity classification schemes

NZHTS classification	Mapping	META classification
Home		<i>n/a</i>
Work: Main Work: Other	$\Sigma$	Employment
Work: Employers Business		<i>n/a</i>
Education	$age < 5$	Preschool
	$5 \leq age < 13$	Primary/Intermediate school
	$13 \leq age < 18$	Secondary school
	$18 < age$	Tertiary education
Shopping		Shopping
Social welfare Personal business	$\Sigma$	Personal business
Medical/dental		Medical/dental
Social visits		Social visits
Recreational		Recreational
Change mode		<i>n/a</i>
Accompany someone		<i>n/a</i>
Left country		<i>n/a</i>
Other		<i>n/a</i>
Overnight lodgings		<i>n/a</i>

### 5.3.1 Minimum saturation values

The trip purpose classifications specified within household travel surveys are designed to provide an overview of travel patterns while avoiding excessive complexity for surveyors and respondents. As a result, the classifications are not as specific as this research would ideally require, particularly when capturing the relatively small-scale effects that may influence active mode travel. For example, the classification Shopping, which is used in New Zealand, United Kingdom and United States surveys, includes a range of specific destinations such as supermarkets, book stores, shoe shops, hardware stores, corner dairies, antique dealers and so on. It is not immediately clear how many facilities would be necessary to fulfil the shopping activity. *Minimum saturation values* are calculated using survey results and real facility locations, and estimate the minimum number of facilities required to actually capture each of the survey activity classifications used in the model. A survey with a fully detailed complement of trip activity classifications would not require this step; although, for the reasons stated above, this is unlikely to occur. Trip activity classifications used in the United States and United Kingdom national household travel surveys are shown in table 5.4 (FHWA, 2009; DfT, 2010) and are similar to those used in the New Zealand survey, shown in table 5.2.

NEW ZEALAND: The minimum saturation values would ideally be calculated at the same level as the travel survey from which they are derived; for example, nationally, as the other constant inputs are. However, when using national travel surveys the activity-classified facilities data is not readily available at the national level. It is also desirable to use the largest sample size possible, for the purpose of reducing sampling errors. As a result, the saturation values dataset has new information appended as facilities are classified when each new sample area is assessed.

Minimum saturation values are applied under the assumption that each of the located activity destinations attracts an equal share of trips to the activity. Consequently, the activity frequency requirement is divided between the number of destinations, and the mode of travel determined separately for each destination.

FOR EXAMPLE: if an activity has a saturation of three and is accessed 60 times per year for the given demography, each destination would attract 20 trips. The first destination may be walkable, the second requiring public transport and the third private vehicle.

#### 5.3.1.1 *Activities*

The saturation value is only meaningful for activity trips originating at the home, and is calculated by the following process:

1. Spatially locate the trip leg origin and destination.
2. Calculate the travel time from the origin to the destination.
3. Generate a travel time ‘radius’ along the network, about the origin, equal to the origin-destination travel time.
4. Count the number of potential facilities, from the classified activity facilities data, that fall within the radius but are not the actual trip destination.
5. Repeat for all surveyed origin-destination pairs.

The example shown in figure 5.4, showing the respondent household, the radius of equal travel time along all networks, and the destination that was actually selected for the shopping activity, produces a saturation of three. This process is repeated for every household trip leg to destination within each activity type. The *minimum* saturation is assumed to be the 25<sup>th</sup> percentile saturation value for all the respondent trips within each activity. A minimum saturation of three means that 25 percent of all surveyed trips to the activity terminate at the closest, or second or third closest facility from the origin. This value is high for broadly defined activities such as shopping, as many of the potential facilities are not actually viable for the majority of trips; for example, a bookshop is not competing with a supermarket when shopping for food, but it still falls within the *shopping* category.

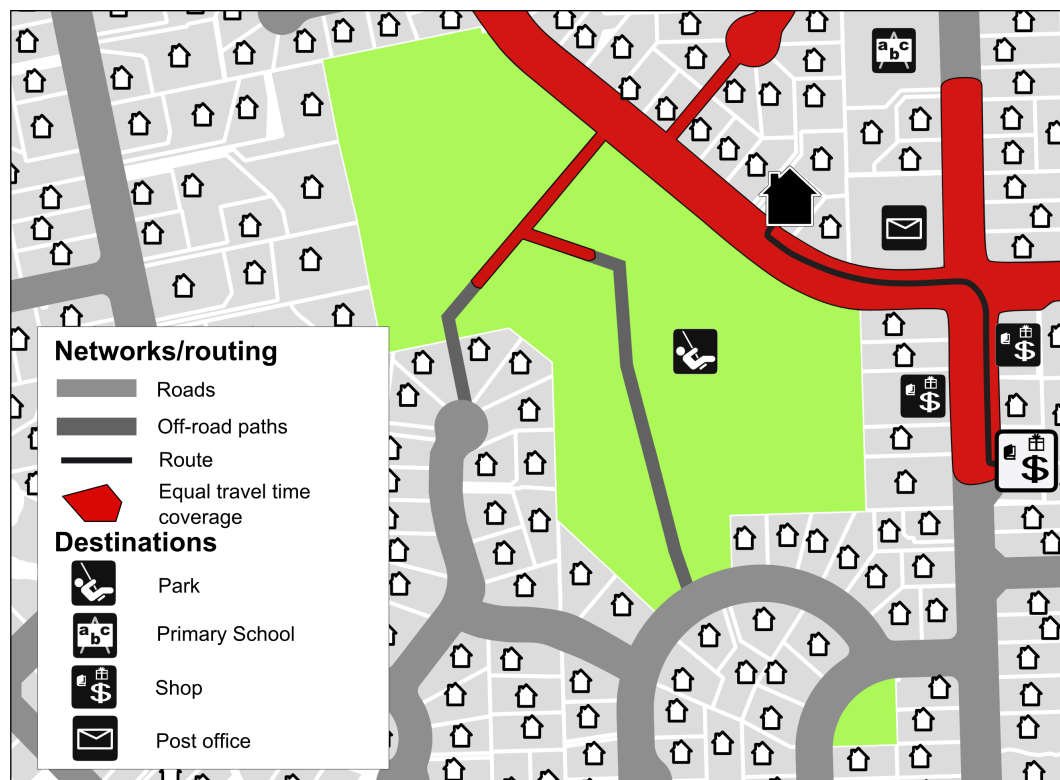
NEW ZEALAND: The minimum saturation values, currently based upon values calculated for the combination of three New Zealand cities; Christchurch, Dunedin and Hamilton, are shown in table 6.2.

#### 5.3.1.2 *Employment*

The minimum saturation for employment is similarly calculated, however, the number of employment opportunities within the travel time radius is counted, rather than the number of facilities.

**Table 5.4:** Trip activity classifications used in the US and UK national household travel surveys (FHWA, 2009; DfT, 2010)

UK activity classifications	US activity classifications
Commuting	Home
Business	Work
Other work	School/Daycare/Religious activity
Education	Medical/Dental services
Shopping	Shopping/Errands
Personal business	Social/Recreational
Social or entertainment	Family personal business/Obligations
Holidays or day trips	Transport someone
Just walk	Meals
Escort trips	Other reason



**Figure 5.4:** Example of saturation value calculation

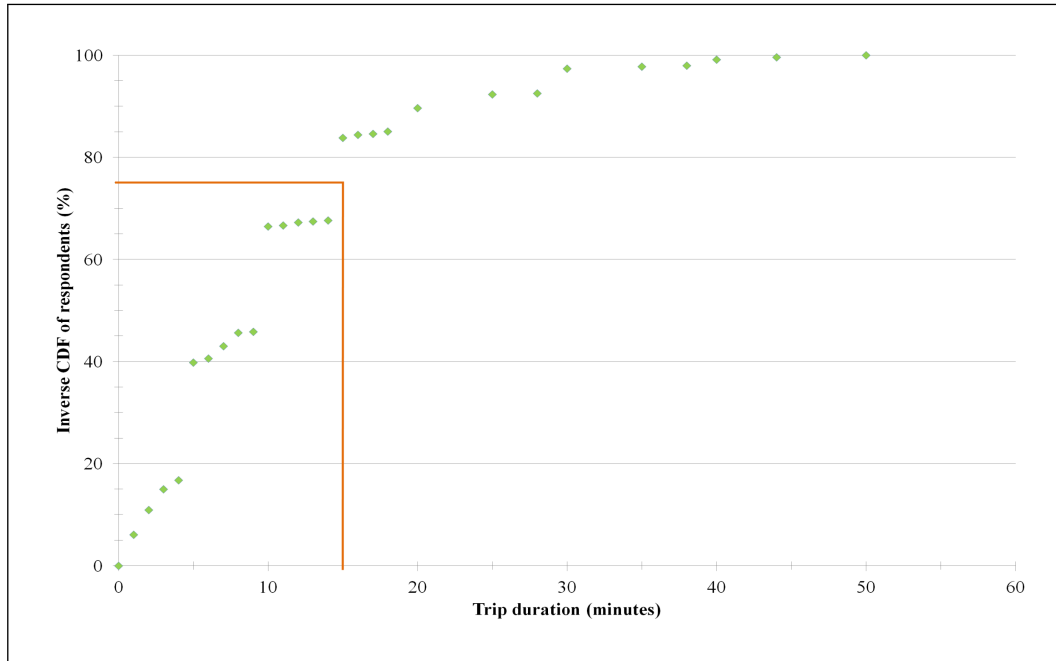
NEW ZEALAND: The 25<sup>th</sup> percentile of potential employment locations, at this stage based upon values calculated for the combination of three New Zealand cities; Christchurch, Dunedin and Hamilton, is 3,800; meaning that 25 percent of all surveyed trips for employment forgo up to 3,800 potential jobs.

### 5.3.2 Mode ability

The amount of time a person of a certain age is able to travel by a mode is termed their *mode ability*; this is assumed to be the 75<sup>th</sup> percentile of travel times for trips made by people of that age. Age groups used in the mode ability calculation are defined to match the available census information. The method for calculating mode ability will vary depending upon the survey design and structure of the provided dataset, although the basic process for a trip-based dataset is:

1. Neglect trips that are:
  - from respondents residing outside desired study area,
  - invalid due to incomplete response,
  - made by professional drivers, or
  - for the purpose of recreation.
2. Categorise trips by respondent age and travel mode.
3. Calculate the 75<sup>th</sup> percentile value within each classification.

NEW ZEALAND: Mode ability values are grouped based upon the New Zealand census convention of five year bins for all ages up to 65, with a final category that contains all respondents over the age of 65. Values have been extracted from the NZHTS through a process of filtering and categorising the input trips dataset, as described above. Only responses from within Major Urban Areas (MUA)s, defined as areas with a population of over 30,000 people, were used. The calculation was implemented through a script developed in the Python programming language. The set of travel time values extracted for the walking trips of 5-9 year old survey respondents is shown in figure 5.5 as a cumulative distribution function, with the 75<sup>th</sup> percentile figure highlighted. The calculated values for all ages and modes are shown in table 6.3.



**Figure 5.5:** Cumulative distribution of walking trip duration for children of 5-9 years of age; 75<sup>th</sup> percentile figure highlighted

### 5.3.3 Activity frequency

The number of times per year that a person of a certain age travels to an activity is termed *activity frequency*. This frequency is assumed to be a necessity, hence the mean number of trips per person within each age group is used. The method for calculating activity frequency will vary depending upon the travel survey design and dataset structure, although the basic process for a dataset with separate trip-based and person-based components is:

1. Neglect trip and person responses that are:
  - from respondents residing outside desired study area,
  - invalid due to incomplete response,
  - made by professional drivers, or
  - for the purpose of recreation.
2. Categorise trips by respondent age and trip purpose (the activity conducted at the destination).
3. Categorise persons by respondent age.



4. Calculate the mean activity frequency per person as the sum of trips to each activity for persons of the specified age group divided by the number of people within the age group.

NEW ZEALAND: Activity frequency values are grouped based upon the New Zealand census convention of five year bins for all ages up to 65, with a final category that contains all respondents over the age of 65. Values have been extracted from the NZHTS through a process of filtering and categorising the input trips and persons datasets, as described above. Only responses from within MUAs were used. The calculation was implemented through a script developed in the Python programming language. The calculated values for all ages and activities are given in tables 6.4 and 6.5.

#### 5.3.4 Trip chaining factor

A trip chain is a combination of trip legs to multiple activities, or by multiple modes, which has a single primary purpose. For example, stopping off at a shop on the way home from work forms a trip chain with two segments and the overall purpose of *Home*. Trip chaining is both part of current travel behaviour, and an adaptive measure. The ability to engage in trip chaining is a complex function of land use patterns, trip purposes and transport systems. Consequently, the method assumes no increase in trip chaining through adaptive measures. The method does account for current levels of trip chaining, although this is done in a non-spatial manner.

The accessibility model underpinning the META method makes the assumption that all trips are home-based, meaning that every trip originates at the home and returns to the home once the activity is complete. Consequently, the annual travel requirement would be twice the distance to the activity multiplied by the activity frequency. This assumption is partially corrected for by instead scaling the frequency by a *trip chaining factor* which is a function of the number of trips a person of a certain age makes to all non-home activities relative to the number of trips they make to home. The trip chaining factor  $C$  is calculated by the equation  $C = 1 + \frac{1}{CP}$ , where the chain proportion CP is calculated by summing the activity frequency of all non-home trips and dividing it by the frequency of trips to home, both calculated as described in section 5.3.3. The trip chaining factor exhibits the following properties:

1. If the survey responses show no chaining is undertaken the factor equals 2.0; meaning that every trip is home-based.

2. As surveyed chaining increases the factor approaches, but never reaches, the value of 1.0

NEW ZEALAND: Trip chaining factor values are grouped based upon the New Zealand census convention of five year bins for all ages up to 65, with a final category that contains all respondents over the age of 65. Values have been calculated based upon the activity frequency values derived from the NZHTS outlined in section 5.3.3, as described above. Only responses from within MUAs were used. The calculation was implemented through a script developed in the Python programming language. The calculated values for all ages and activities are given in table 6.6.

### 5.3.5 Modal energy intensity

Public transport and private vehicle occupancy rate increases have been neglected. Consequently, modal energy intensity figures are assumed to be constant and equivalent to the most representative New Zealand data available, in this case 1990 average values for Australian cities as described in section 4.4. These values are 1.68 Megajoules per passenger-kilometre ( $\frac{MJ}{p-km}$ ) for bus public transport and  $3.02\frac{MJ}{p-km}$  for private vehicles.

## 5.4 META algorithm

The method for calculating the META minimum energy consumption is outlined in figure 5.1. This section describes each of the model components in detail, utilising and building upon the study area inputs described in section 5.2 and constant inputs described in section 5.3. The output section of each component describes the minimum required output for the model, other attributes such as unique identifiers for points or areas may also be stored for later reference and displaying results.

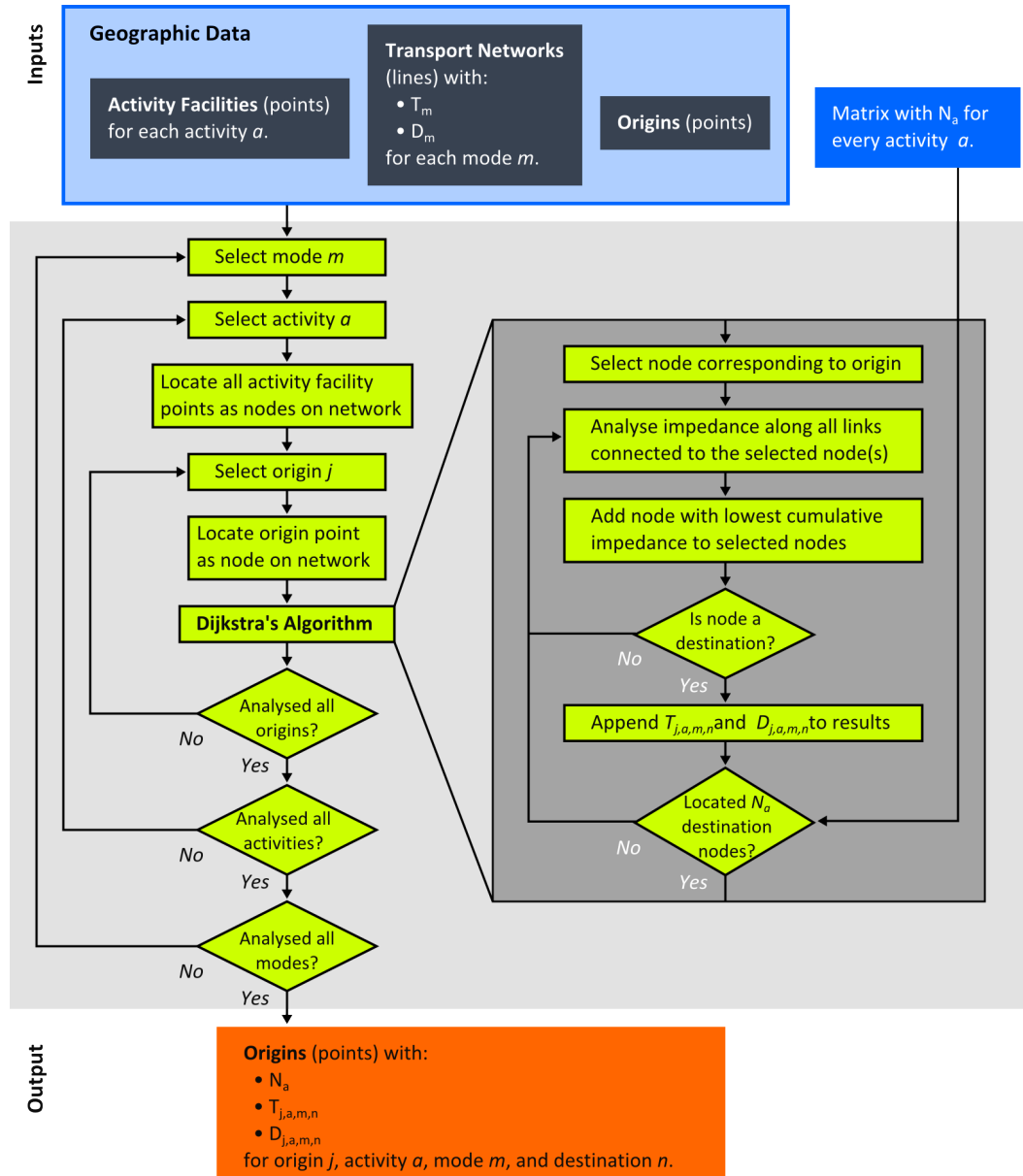
### 5.4.1 Origin-destination routes calculation

Travel time and distance along each network is calculated from every origin to the saturation number of destinations for all activities by the method shown in figure 5.6. Inputs to the calculation are:

1. Activity facility points; classified according to travel survey definitions.
2. Transport networks in graph representation.

3. Origin points; no attributes required.
4. Matrix of minimum saturation value for each activity.

Mode and activity are selected, and the activity facilities are located as special nodes on the network. Next, an origin is selected and the origin point is located as the origin node on the network. The original Dijkstra's Algorithm calculates the shortest path between the origin node on a network and all the other nodes. For this application it has been modified to record both time and distance values for each destination node that is located and end the calculation once the specified number of destination nodes have been found. The calculation iterates through all combinations of origin, activity and mode. The only output is the origin points dataset with saturation values for every activity ( $N_a$ ), and travel time and distance to every activity destination by mode ( $T_{j,a,m,n}$ ,  $D_{j,a,m,n}$ ).



**Figure 5.6:** Schematic diagram of origin-destination routes calculation

### 5.4.2 Assign demography to origins

The implementation of the model assumes that population demography is typical and constant within census areas; consequently, each household is assigned the average population and age profile of the area. The assignment method is described in figure 5.7. Inputs to the calculation are:

1. Census boundaries; which should be at the finest resolution available with a low proportion of confidentialised units. Required to include demographic data of both number of persons within age bins ( $P_{i,k}$ ) and number of households in area ( $H_k$ ).
2. Origin points with saturation values for every activity ( $N_a$ ), and travel time and distance to every activity destination by mode ( $T_{j,a,m,n}$ ,  $D_{j,a,m,n}$ ).

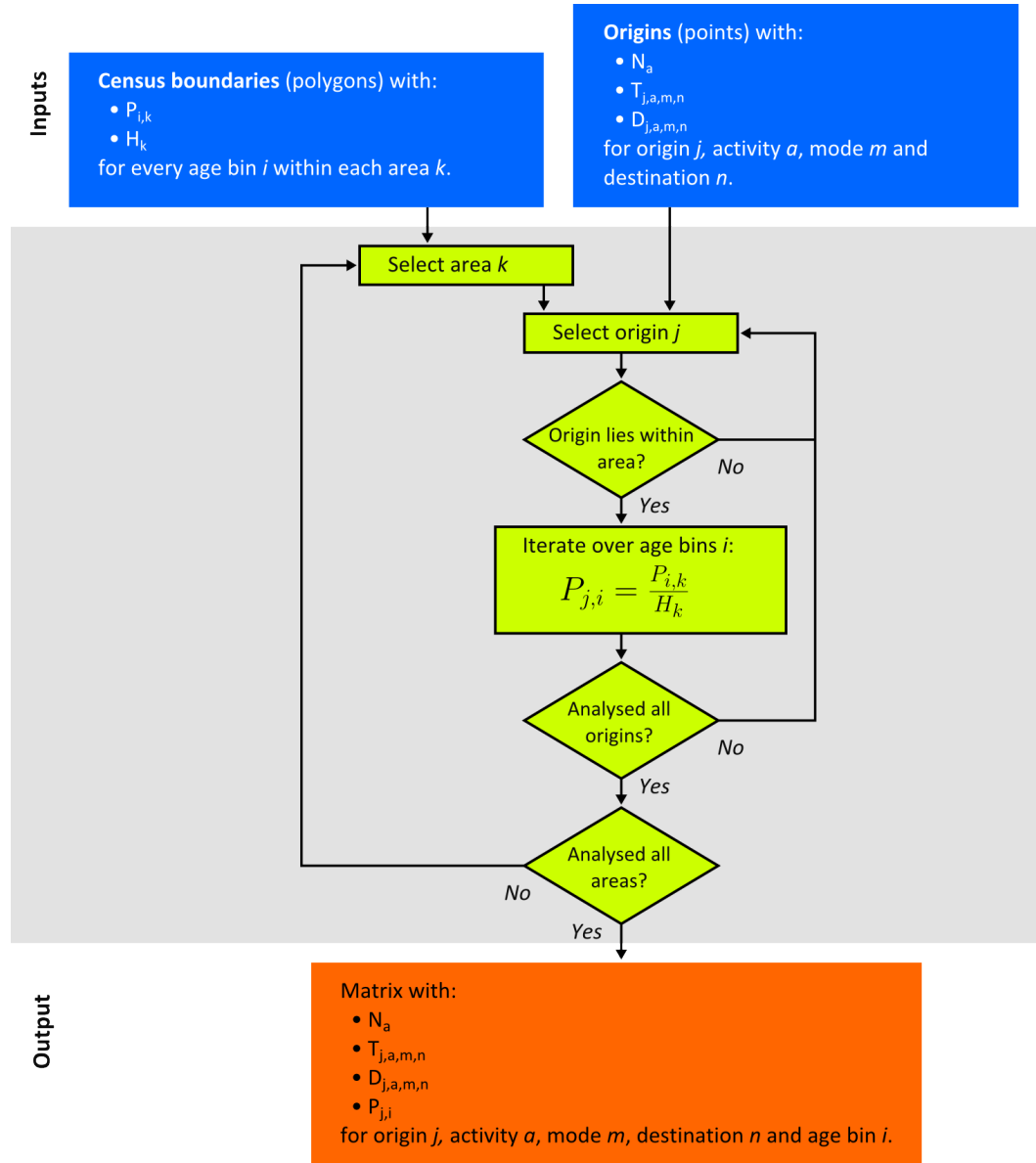
An area is selected, then each origin location spatially analysed for intersection with the area. If the origin lies within the area, the household is assigned a population demography equivalent to the average profile and number of persons per household within the area.

FOR EXAMPLE: if an area with 1,000 households has 200 residents aged between 25 and 29, all households in the area are assigned a population of 0.2 residents in the age bin 25 to 29.

The calculation iterates through all areas and origins. The remainder of the method does not require a spatial element, hence the output is a matrix containing every origin as a separate row and the following columns:

- saturation values for each activity ( $N_a$ ),
- travel time to every activity destination by mode ( $T_{j,a,m,n}$ ),
- travel distance to every activity destination by mode ( $D_{j,a,m,n}$ ), and
- population demography for every age bin ( $P_{j,i}$ ).

For display of the final results, the matrix can be joined to the origin points or summed directly to the relevant census areas by unique identifier.



**Figure 5.7:** Schematic diagram of origin demography assignment

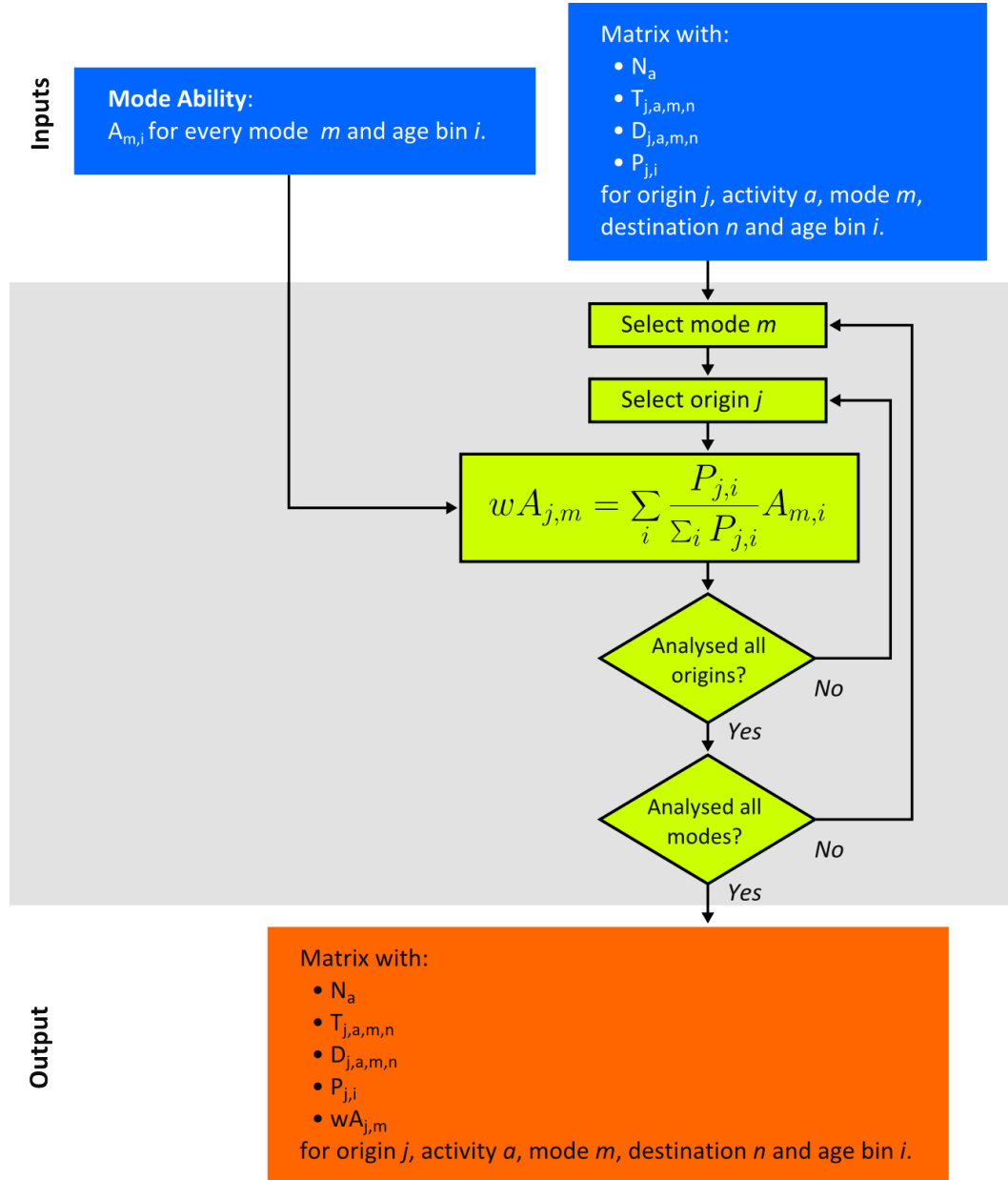
### 5.4.3 Mode ability weighting

Mode ability is assigned to households as a function of resident demography and nationally-derived mode abilities by age; as outlined in figure 5.8. Inputs to the calculation are:

1. Mode ability for every mode and age bin ( $A_{m,i}$ ).
2. Outputs of the previous calculation; a matrix of origins (rows) with columns of:
  - saturation values for each activity ( $N_a$ ),
  - travel time to every activity destination by mode ( $T_{j,a,m,n}$ ),
  - travel distance to every activity destination by mode ( $D_{j,a,m,n}$ ), and
  - population demography for every age bin ( $P_{j,i}$ ).

The calculation iterates through modes and origins; then computes the weighted mode ability as the sum of proportion of residents by age multiplied by mode ability for each age. The output is a matrix of origins (rows) with columns of:

- saturation values for each activity ( $N_a$ ),
- travel time to every activity destination by mode ( $T_{j,a,m,n}$ ),
- travel distance to every activity destination by mode ( $D_{j,a,m,n}$ ),
- population demography for every age bin ( $P_{j,i}$ ), and
- weighted mode ability for every mode ( $wA_{j,m}$ ).



**Figure 5.8:** Schematic diagram of mode ability weighting calculation



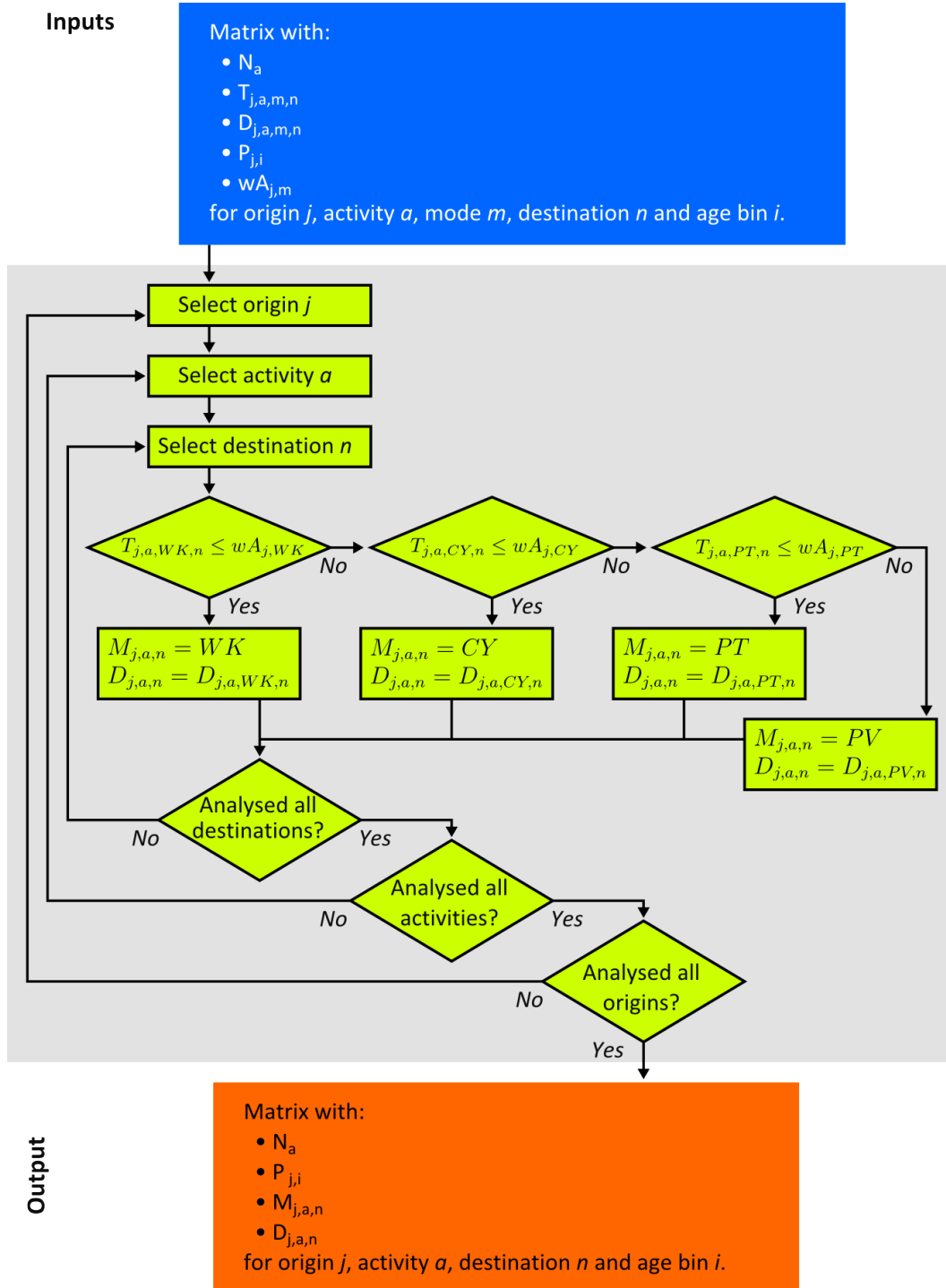
#### 5.4.4 Minimum energy mode assignment

Travel from origins to destinations is assumed to have the potential to be made by the least energy intensive mode within the ability of the residents, which is determined through the minimum energy mode hierarchy. Mode ability effectively defines the threshold of the stepwise impedance function for accessibility by each mode. The method by which the minimum energy mode is determined is outlined in figure 5.9. The only input to the calculation is the output of the previous calculation, a matrix of origins as rows with columns of:

- saturation values for each activity ( $N_a$ ),
- travel time to every activity destination by mode ( $T_{j,a,m,n}$ ),
- travel distance to every activity destination by mode ( $D_{j,a,m,n}$ ),
- population demography for every age bin ( $P_{j,i}$ ), and
- weighted mode ability for every mode ( $wA_{j,m}$ ).

An origin is selected, then an activity, then one of the destinations which was located for that origin. Each iteration through the core of the calculation represents one possible *trip leg* from the origin to a destination. The route from the origin to the destination is first assessed to determine if the travel time by walking is within the walking ability of the residents. If the walking time is within the resident walking ability, the mode for that trip is set to walk ( $WK$ ) and the distance from the origin to that destination is set to the distance covered along the walking network in reaching that destination. If the travel time exceeds the resident ability the same test is performed for cycling and public transport, and the mode and distance are set accordingly. If the time exceeds the abilities for all of walking, cycling and public transport, the mode is assumed to be private vehicle and the distance and mode variables are set accordingly. The calculation iterates through origins, activities and destinations. The output of the calculation is a matrix of origins as rows with columns of:

- saturation values for each activity ( $N_a$ ),
- population demography for every age bin ( $P_{j,i}$ ),
- travel mode for origin to every activity destination ( $M_{j,a,n}$ ), and
- travel distance for origin to every activity destination ( $D_{j,a,n}$ ).



**Figure 5.9:** Schematic diagram of minimum energy mode calculation

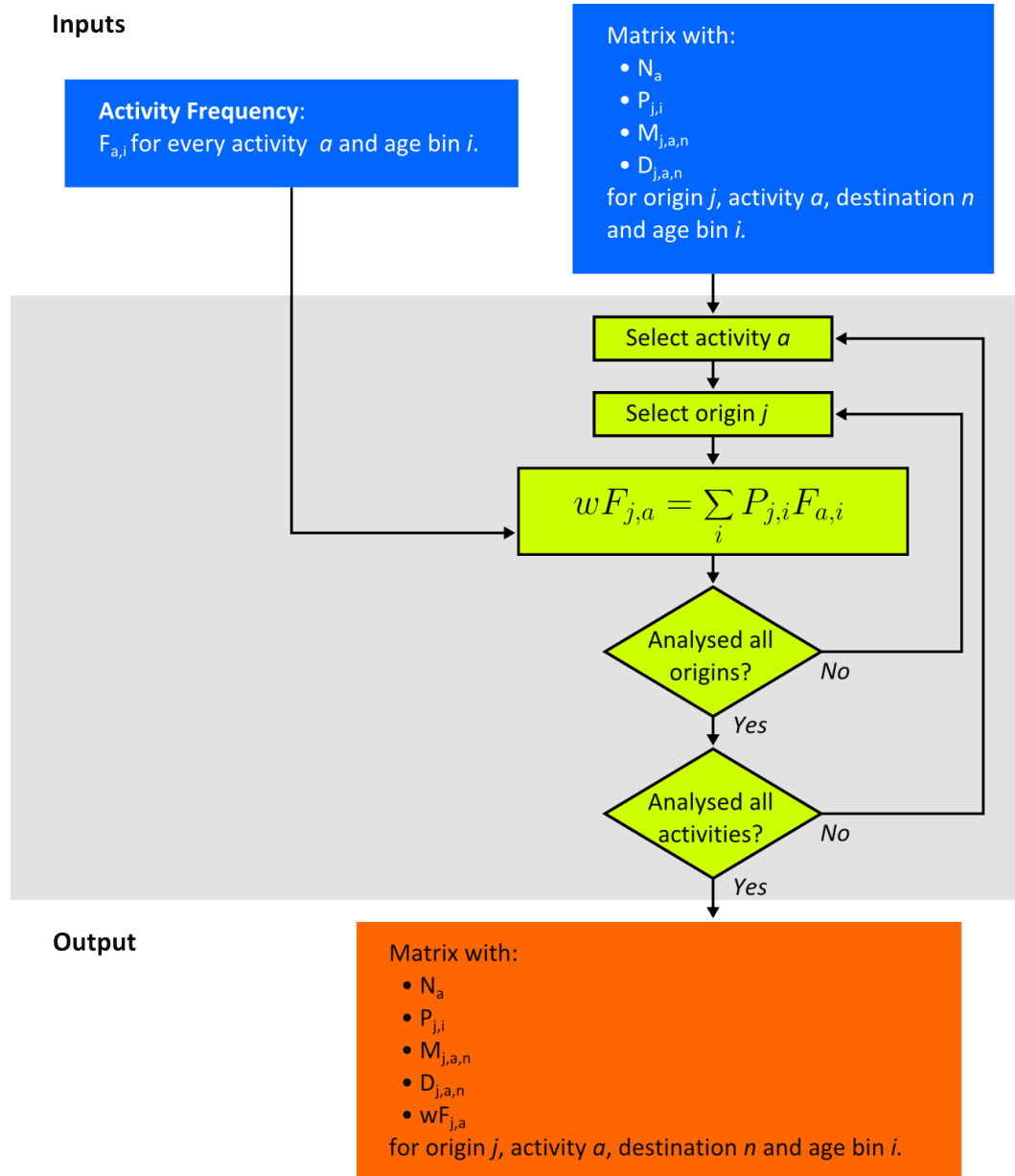
### 5.4.5 Activity frequency weighting

Activity frequency is assigned to households as a function of resident demography and nationally-derived activity frequencies by age; as outlined in figure 5.10. Inputs to the calculation are:

1. Activity frequency for every activity and age bin ( $F_{a,i}$ ).
2. Outputs of the previous calculation; a matrix of origins (rows) with columns of:
  - saturation values for each activity ( $N_a$ ),
  - population demography for every age bin ( $P_{j,i}$ ),
  - travel mode for origin to every activity destination ( $M_{j,a,n}$ ), and
  - travel distance for origin to every activity destination ( $D_{j,a,n}$ ).

The calculation iterates through activities and origins; then calculates the weighted activity frequency as the sum of residents by age multiplied by activity frequency for each age. The output is a matrix of origins as rows, with columns of:

- saturation values for each activity ( $N_a$ ),
- population demography for every age bin ( $P_{j,i}$ ),
- travel mode for origin to every activity destination ( $M_{j,a,n}$ ),
- travel distance for origin to every activity destination ( $D_{j,a,n}$ ), and
- weighted activity frequency for every activity ( $wF_{j,a}$ ).



**Figure 5.10:** Schematic diagram of activity frequency weighting calculation

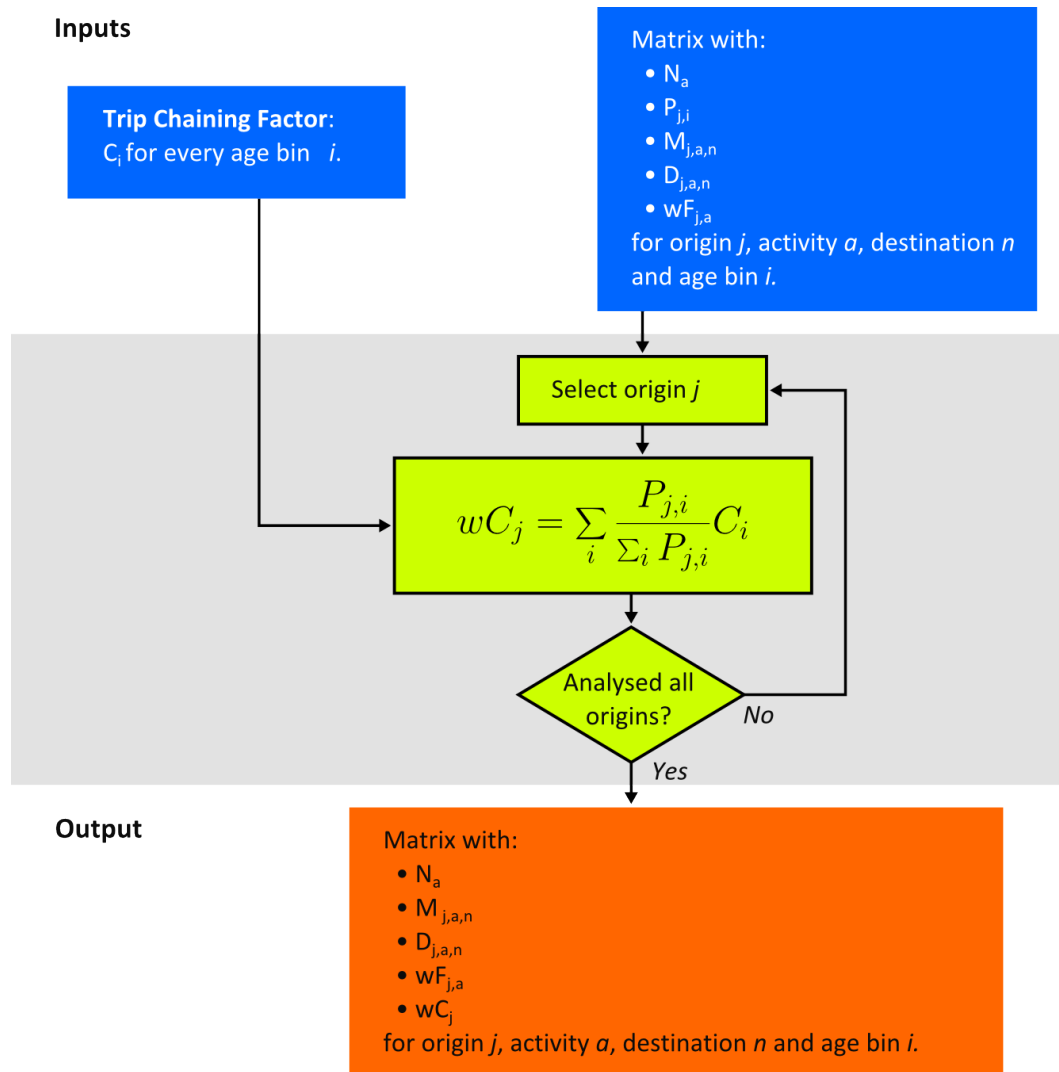
### 5.4.6 Trip chaining factor weighting

Trip chaining is assigned to households as a function of resident demography and nationally-derived trip chaining factors by age; as outlined in figure 5.11. Inputs to the calculation are:

1. Trip chaining factors for every age bin ( $C_i$ ).
2. Outputs of the previous calculation; a matrix of origins (rows) with columns of:
  - saturation values for each activity ( $N_a$ ),
  - population demography for every age bin ( $P_{j,i}$ ),
  - travel mode for origin to every activity destination ( $M_{j,a,n}$ ),
  - travel distance for origin to every activity destination ( $D_{j,a,n}$ ), and
  - weighted activity frequency for every activity ( $wF_{j,a}$ ).

The calculation iterates through origins; then calculates the weighted chaining factor as the sum of proportion of residents by age multiplied by chaining factor for each age. The output is a matrix of origins as rows, with columns of:

- saturation values for each activity ( $N_a$ ),
- travel mode for origin to every activity destination ( $M_{j,a,n}$ ),
- travel distance for origin to every activity destination ( $D_{j,a,n}$ ),
- weighted activity frequency for every activity ( $wF_{j,a}$ ), and
- weighted trip chaining factor ( $wC_j$ ).



**Figure 5.11:** Schematic diagram of trip chaining factor weighting calculation

### 5.4.7 META minimum energy calculation

Household minimum energy consumption is calculated for energy consuming modes as the product of distance to activity, energy consumption of the mode and the frequency with which the activity is accessed. The calculation process is outlined in figure 5.12. The only input to the calculation is the output of the previous calculation, a matrix of origins as rows with columns of:

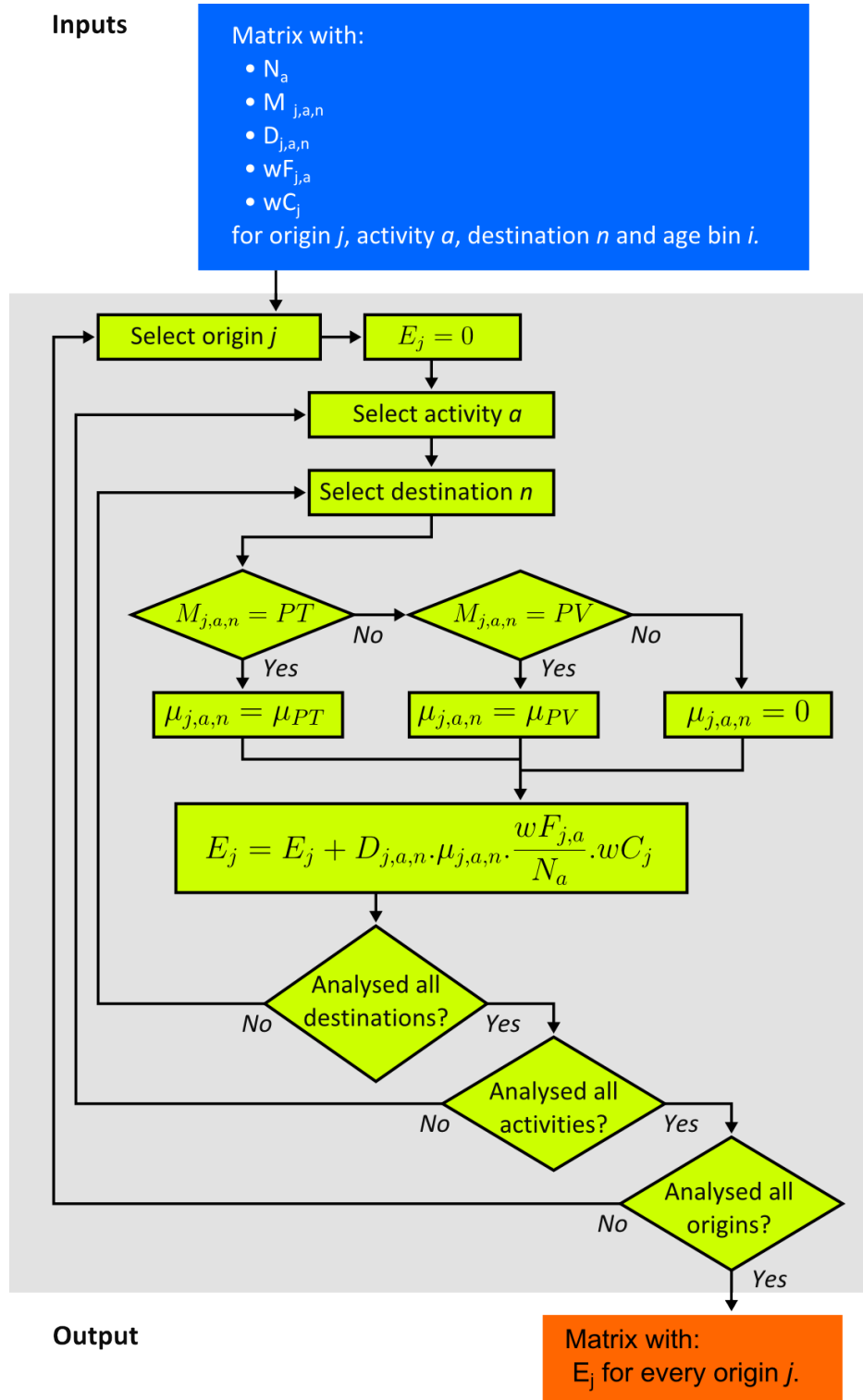
- saturation values for each activity ( $N_a$ ),
- travel mode for origin to every activity destination ( $M_{j,a,n}$ ),
- travel distance for origin to every activity destination ( $D_{j,a,n}$ ),
- weighted activity frequency for every activity ( $wF_{j,a}$ ), and
- weighted trip chaining factor ( $wC_j$ ).

The calculation iterates through origins, initially setting the minimum energy consumption for the origin to zero. Then an activity and destination are selected. The value of the energy intensity variable for the trip is determined by the mode of travel in the following fashion:

1. If the mode is walking or cycling the value of the energy intensity is set to zero, effectively setting the energy consumption for that origin-destination pair to zero.
2. If the mode of travel between the origin and the specific destination is public transport, the energy intensity of the origin to destination trip is set to the effective energy intensity of the public transport mode ( $\mu_{PT}$ ),  $1.68 \frac{MJ}{p-km}$  (Newman & Kenworthy, 1999).
3. Otherwise, if the mode is private vehicle, the energy intensity is set to the private vehicle energy intensity ( $\mu_{PV}$ ),  $3.02 \frac{MJ}{p-km}$  (Newman & Kenworthy, 1999).

Travel is generated at the individual level within the household, hence each kilometre of travel calculated by the model represents one passenger-kilometre of travel.

The META minimum energy consumption is the product of distance, energy intensity and *scaled destination frequency*. The *destination frequency* is the activity frequency divided by the saturation value for the activity; based upon the assumption that each of the located activity destinations attracts an equal share of trips to the activity. This value is then scaled by the *weighted trip chaining factor*. Minimum



**Figure 5.12:** Schematic diagram of minimum energy calculation



energy is accumulated for all activities and destinations accessed by the origin, then the origin is iterated.

The output is a single minimum energy value ( $E_j$ ) for every origin within the study area ( $j$ ). The contribution of each activity ( $a$ ) and mode ( $M$ ) to the total household minimum energy value may be stored in a matrix for later analysis. If appropriate spatial data, or unique identifiers, are retained with the data, the household-level results can be displayed directly on a map, or summed or averaged within areas.

## 5.5 META implementation

The META analysis has been developed in conjunction with Abley Transportation Consultants Limited, and implemented as an extension to the NZTA accessibility methodology detailed by [Abley and Halden \(2012\)](#). The Origin-destination routes calculation is written in the Python programming language making use of Esri ArcGIS through the Arcpy site-package to interface with geographic data and Esri Network Analyst to perform network calculations<sup>2</sup>. The remainder of the program is written in the Python programming language, making use of the Arcpy site-package to interface with geographic data.

### 5.5.1 List of META data sources

The META method data sources described within this chapter for both study area and nationally constant inputs are listed in tables 5.5 and 5.6, respectively. The nationally constant inputs are somewhat dependent upon implementation assumptions, which may be influenced by external factors such as travel survey activity classification schemes.

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<sup>2</sup>Further information regarding each package can be found on the following websites:

- Python: <http://www.python.org/>
- Esri ArcGIS: <http://www.esri.com/software/arcgis/index.html>
- Arcpy: <http://help.arcgis.com/en/arcgisdesktop/10.0/help/index.html#//000v000000v7000000>
- Network Analyst: <http://www.esri.com/software/arcgis/extensions/networkanalyst/index.html>

**Table 5.5:** List of data sources for META study area inputs and New Zealand examples

Item	Details	Described in section	New Zealand source
Origins	Points representing households	5.2.2	Land Information New Zealand (LINZ) Core Record System address points
Activity facilities	Points representing activity facilities, manually classified to match activities used in nationally constant inputs	5.2.3	<a href="http://www.Zenbu.co.nz">http://www.Zenbu.co.nz</a> collaboratively edited directory of businesses and places
Employment facilities	Points representing employment facilities, including opportunities count	5.2.4	Statistics New Zealand Business Units Dataset
Transport networks	Lines representing transport networks	5.2.5	Modified version of LINZ Road Centrelines dataset
Demographic data	Census data of age profiles within areas	5.2.1	Statistics New Zealand Census Meshblock Dataset

**Table 5.6:** List of data sources for META nationally constant inputs and New Zealand examples

Item	Details	Described in section	New Zealand source
Mode ability	Age based population ability to use non-car modes	5.3.2	New Zealand Household Travel Survey (NZHTS)
Activity frequency	Age based frequency of activity access	5.3.3	NZHTS
Chain weighting	Age based level of trip chaining currently undertaken	5.3.4	NZHTS
Minimum saturation values	Representation of the minimum number of facilities required to attain an activity	5.3.1	Combination of NZHTS and classified Activity facilities data
Modal energy intensity values	Megajoules consumed per passenger-kilometre by public transport and private vehicle modes	5.3.5	Newman and Kenworthy (1999) modal energy intensity values for Australian cities (1990 data)



## CHAPTER 6

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# CASE STUDIES

The Minimum Energy Transport Adaptability (META) analysis has been applied to two New Zealand case studies. This chapter presents the national-level constant inputs calculated for New Zealand, and the study area inputs and results for the cities of Christchurch and Hamilton.

### 6.1 New Zealand Constant Inputs

The constant inputs of minimum saturation values, mode abilities, activity frequencies and trip chaining used in the case studies were derived from the New Zealand Household Travel Survey (NZHTS) and classified destinations data, using the methods described in section 5.3.

Minimum saturation values, fully described in section 5.3.1, are the 25<sup>th</sup> percentile number of destinations required to capture an activity as defined by the NZHTS. The minimum saturation values were calculated within the three New Zealand cities that have had destinations appropriately classified: Dunedin, Christchurch and Hamilton. The values for each city are displayed in table 6.1, and overall results actually used within the model are displayed in table 6.2. Overall values are the 25<sup>th</sup> percentile value of the combined raw cities data, effectively weighting the overall value by the number of surveyed trips from each city.

Mode ability values, fully described in section 5.3.2, are the 75<sup>th</sup> percentile time that persons within each census age group travel. These values were derived from the NZHTS dataset at the MUA level, and are presented in table 6.3. Mode abilities for public transport include the time taken for walking trips at either side of the public

**Table 6.1:** Minimum saturation values calculated within New Zealand cities, sample size indicated in parentheses

Activity	Minimum saturation value (trip chains)		
	Dunedin	Christchurch	Hamilton
Preschool	2 (7)	4 (34)	11 (13)
Primary/Intermediate School	4 (8)	3 (75)	2 (18)
Secondary School	2 (19)	2 (51)	5 (11)
Tertiary Education	1 (24)	2 (96)	1 (18)
Medical/Dental	1 (16)	16 (38)	5 (15)
Personal business	29 (106)	28 (274)	7 (91)
Recreation	1 (120)	1 (416)	1 (61)
Shopping	54 (304)	68 (1,091)	56 (243)
Social visits	49 (88)	16 (261)	31 (46)
Employment (jobs)	2,400 (187)	5,500 (564)	3,600 (119)

**Table 6.2:** Overall minimum saturation values calculated for New Zealand cities, as used in the model, sample size indicated in parentheses

Activity	Minimum saturation value (trip chains)
Preschool	4 (54)
Primary/Intermediate School	2 (101)
Secondary School	2 (81)
Tertiary Education	1 (138)
Medical/Dental	8 (69)
Personal business	26 (471)
Recreation	1 (597)
Shopping	62 (1,638)
Social visits	20 (395)
Employment (jobs)	3,800 (870)

transport journey.

Annual frequencies of activity access, fully described in section 5.3.3, are the number of times per year that persons of each census age group travel to different activities. These values were similarly derived from the NZHTS at the MUA level and are presented in tables 6.4 and 6.5.

Trip chaining factors, fully described in section 5.3.4, are the ratio of trips to activities versus trips to home undertaken by persons within each census age group. These values were derived from the NZHTS at the MUA level and are presented in table 6.6.

**Table 6.3:** Mode ability values calculated for New Zealand cities, sample size indicated in parentheses

Age group	Mode ability [min] (trip chains)		
	Walk	Cycle	Public Transport
0-4	15 (195)	19 (10)	40 (14)
5-9	15 (495)	15 (81)	30 (52)
10-14	15 (827)	20 (268)	36 (179)
15-19	20 (685)	15 (110)	40 (258)
20-24	20 (472)	15 (59)	40 (149)
25-29	21 (311)	30 (47)	37 (90)
30-34	20 (314)	20 (67)	50 (74)
35-39	20 (348)	24 (81)	38 (56)
40-44	20 (309)	25 (72)	39 (77)
45-49	21 (433)	28 (94)	36 (57)
50-54	20 (338)	35 (56)	48 (54)
55-59	23 (334)	25 (30)	44 (46)
60-64	20 (299)	24 (37)	41 (25)
$\geq 65$	20 (1,087)	20 (58)	39 (131)



**Table 6.4:** Education activity frequency values calculated for New Zealand cities, sample sizes indicated in parentheses

Age group (persons)		Annual frequency (trip chains)			
		Preschool	Primary/ Intermediate School	Secondary School	Tertiary Education
0-4	(1,774)	187 (1,744)	0 (0)	0 (0)	0 (0)
5-9	(1,584)	0 (0)	224 (1,866)	0 (0)	0 (0)
10-14	(1,617)	0 (0)	129 (1,088)	83 (748)	0 (0)
15-19	(1,521)	0 (0)	0 (0)	107 (899)	54 (370)
20-24	(1,371)	0 (0)	0 (0)	0 (0)	74 (534)
25-29	(1,338)	0 (0)	0 (0)	0 (0)	23 (150)
30-34	(1,486)	0 (0)	0 (0)	0 (0)	17 (119)
35-39	(1,647)	0 (0)	0 (0)	0 (0)	14 (127)
40-44	(1,611)	0 (0)	0 (0)	0 (0)	11 (95)
45-49	(1,631)	0 (0)	0 (0)	0 (0)	10 (72)
50-54	(1,370)	0 (0)	0 (0)	0 (0)	8 (42)
55-59	(1,158)	0 (0)	0 (0)	0 (0)	4 (29)
60-64	(1,068)	0 (0)	0 (0)	0 (0)	5 (21)
≥ 65	(3,156)	0 (0)	0 (0)	0 (0)	2 (39)

**Table 6.5:** Non-education activity frequency values calculated for New Zealand cities, sample sizes indicated in parentheses

Age group (persons)	Annual frequency (trip chains)						
	Employment	Medical/ Dental	Personal business	Recreation	Shopping	Social visits	
0-4	(1,774)	0 (0)	8 (66)	6 (62)	55 (513)	23 (194)	0 (0)
5-9	(1,584)	1 (6)	3 (23)	11 (108)	85 (793)	45 (418)	119 (1,109)
10-14	(1,617)	3 (25)	3 (40)	23 (203)	114 (1,030)	85 (743)	145 (1,375)
15-19	(1,521)	92 (635)	5 (42)	41 (311)	85 (782)	148 (1,248)	186 (1,672)
20-24	(1,371)	171 (1,184)	7 (45)	70 (493)	68 (496)	184 (1,439)	234 (1,697)
25-29	(1,338)	200 (1,423)	10 (65)	81 (565)	81 (510)	210 (1,579)	203 (1,471)
30-34	(1,486)	189 (1,535)	12 (91)	93 (665)	80 (646)	238 (1,944)	173 (1,425)
35-39	(1,647)	194 (1,702)	12 (102)	105 (826)	88 (785)	233 (2,240)	168 (1,554)
40-44	(1,611)	236 (1,891)	7 (83)	110 (875)	96 (853)	231 (2,216)	155 (1,479)
45-49	(1,631)	213 (1,978)	12 (106)	115 (928)	98 (954)	269 (2,386)	162 (1,437)
50-54	(1,370)	213 (1,557)	11 (101)	135 (831)	84 (677)	285 (2,046)	171 (1,273)
55-59	(1,158)	194 (1,264)	17 (91)	106 (614)	113 (693)	276 (1,697)	169 (1,061)
60-64	(1,068)	154 (955)	14 (88)	102 (624)	94 (547)	268 (1,540)	174 (951)
≥ 65	(3,156)	24 (431)	29 (460)	108 (1,739)	97 (1,652)	241 (4,210)	154 (2,673)

**Table 6.6:** Trip chaining factor values calculated for New Zealand cities, sample sizes indicated in parentheses

Age group	Trip chaining factor (persons)
0-4	1.85 (1,774)
5-9	1.92 (1,584)
10-14	2.00 (1,617)
15-19	2.19 (1,521)
20-24	2.43 (1,371)
25-29	2.20 (1,338)
30-34	2.29 (1,486)
35-39	2.19 (1,647)
40-44	2.33 (1,611)
45-49	2.26 (1,631)
50-54	2.32 (1,370)
55-59	2.36 (1,158)
60-64	2.13 (1,068)
$\geq 65$	1.94 (3,156)

## 6.2 Christchurch

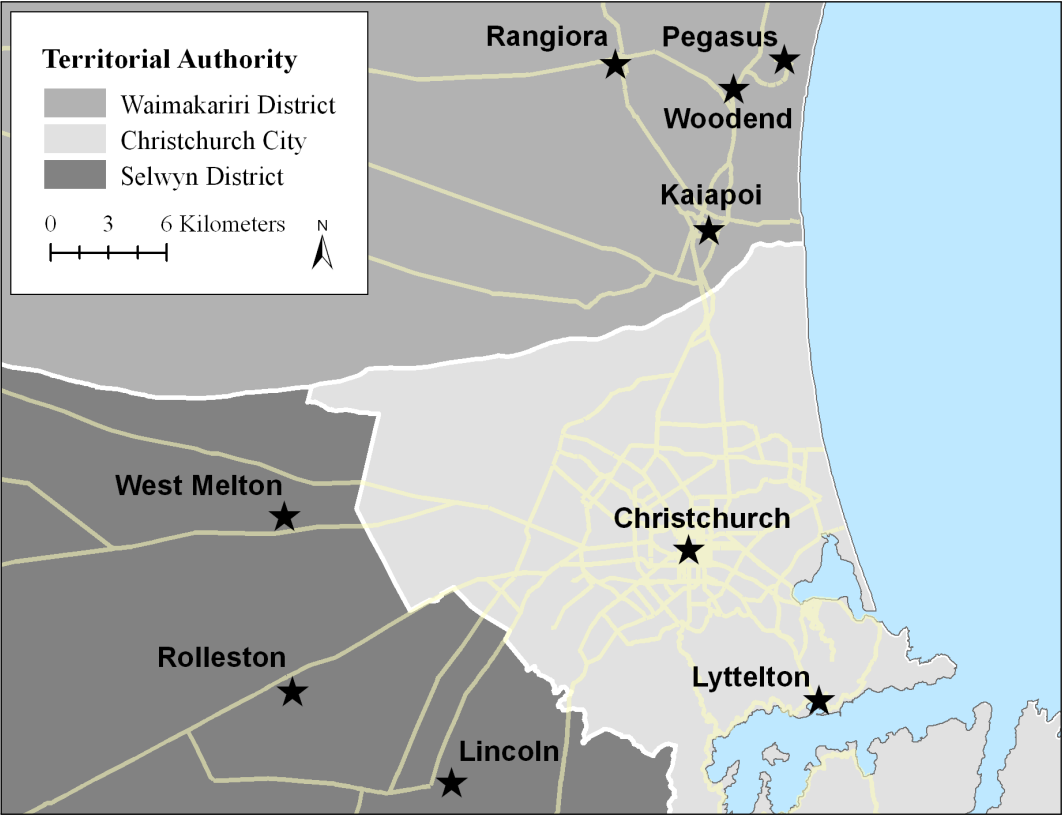
Christchurch is the largest city in New Zealand's South Island with a population of over 380,000 people in 120,000 households and a land area of 450 km<sup>2</sup>. The study area is somewhat smaller than the metropolitan area boundary and has an effective urban residential density of 14.3 persons per hectare. This study is based upon Christchurch data prior to the significant earthquakes of September 4<sup>th</sup>, 2010, and February 22<sup>nd</sup>, 2011.

Christchurch is the regional centre for a number of satellite communities, as shown in figure 6.1. All of these towns, with the exception of Lyttelton, lie outside the jurisdiction of the Christchurch City Council. West Melton and Pegasus were both recently developed as satellite commuter towns, Rolleston was designed to provide workers for a nearby industrial park but has since seen significant population growth, while the other communities were pre-existing towns that have since grown. The population of most of these communities is increasing, and is expected to continue growing in the near future, as a result of the recent earthquakes which have left parts of Christchurch uninhabitable. These towns exhibit a high level of commuting into Christchurch, primarily by private vehicle for the purposes of employment and shopping.

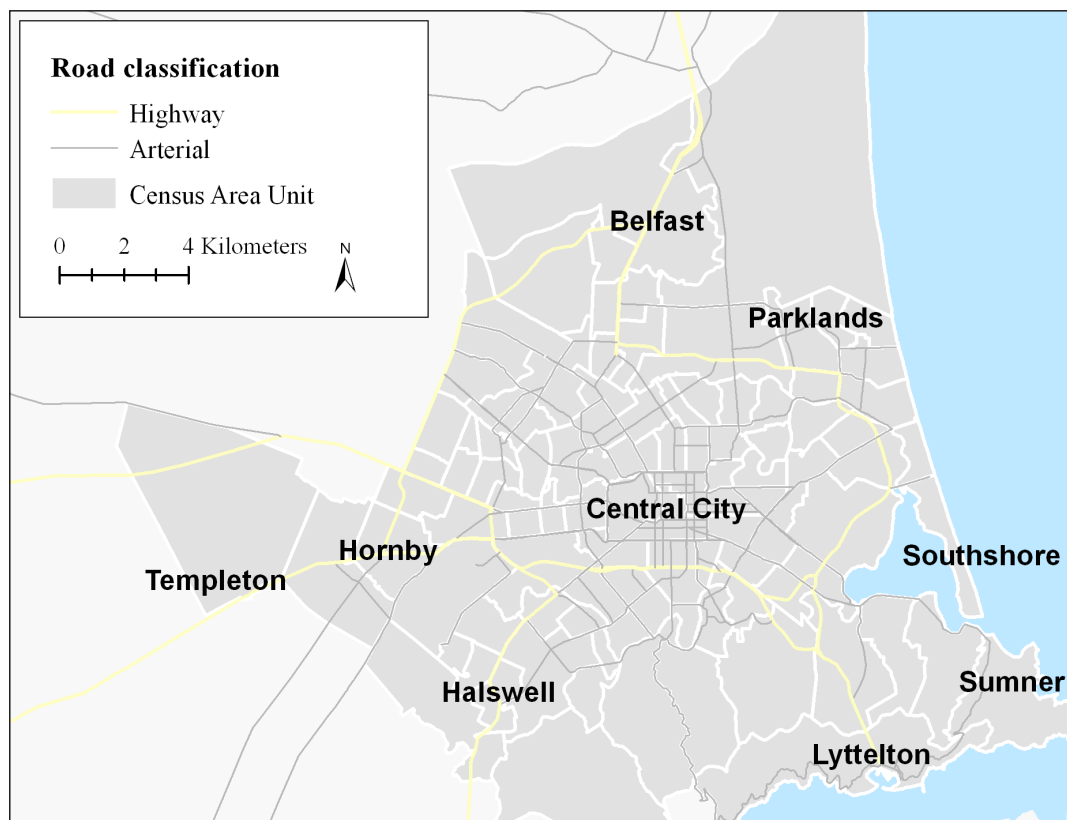
Demographic data is utilised at the census Area Unit level to attain the highest resolution while minimising the number of confidential units. The boundaries of these units are shown in figure 6.2 along with key areas and major roads in Christchurch. The census boundary data was trimmed to fit the available origins data, rather than the Christchurch City Council boundary.

The highest residential population densities are situated radially about the city centre, while the core is predominantly non-residential; medium to low density areas typify the city limits, with a few exceptions, as shown in figure 6.3. Key Activity Centres (KACs), defined by Environment Canterbury (2007, p. 7) as “keycentresof-businessandserviceactivity” that are “highlyaccessibleandconstitutenodesonthe strategic-transportnetworks”, provide an indication of where activity facilities are clustered. KACs are relatively evenly situated around Christchurch, also shown in figure 6.3.

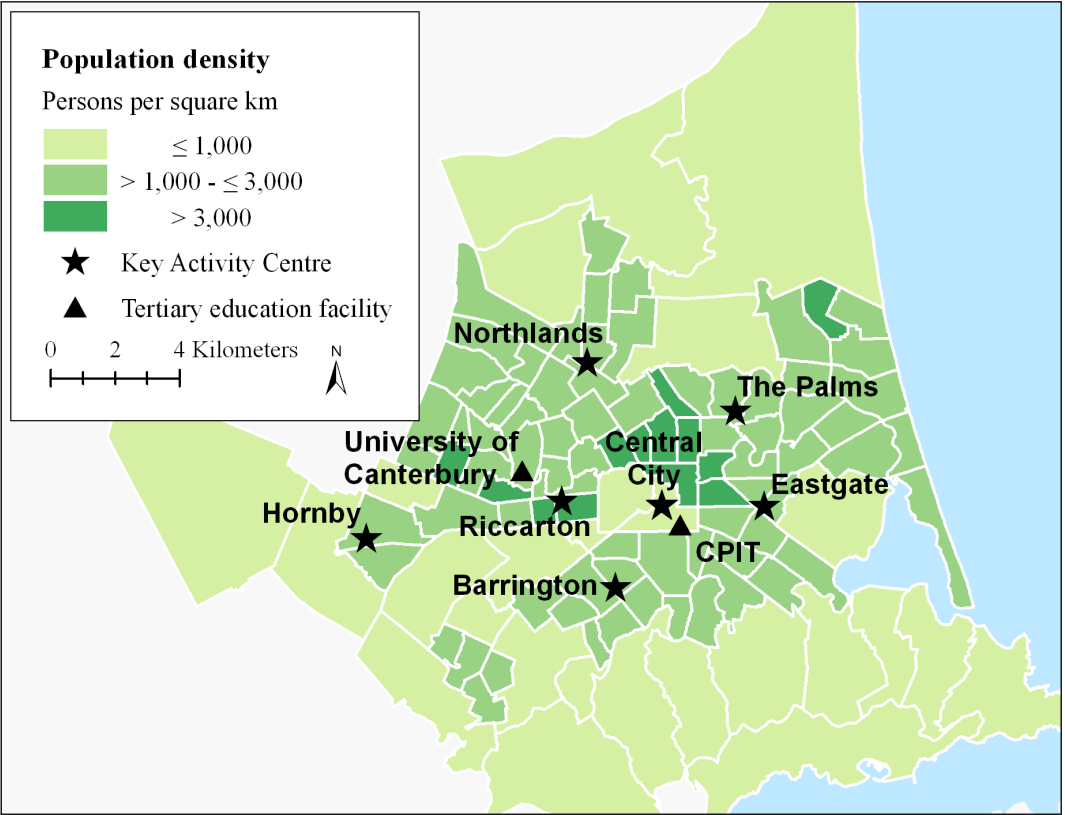
Christchurch itself is predominantly flat although the Port hills to the south, which contain some residential suburbs, separate the city from the major port of Lyttelton, as shown in figure 6.4. A tunnel between Lyttelton and Christchurch provides direct access to the port.



**Figure 6.1:** Christchurch region: satellite communities proximate to Christchurch, Territorial Authority jurisdictions and major roads



**Figure 6.2:** Christchurch city census Area Units, major roads and key outlying suburbs



**Figure 6.3:** Christchurch city population density at census Area Unit level, Key Activity Centres and Tertiary education facilities



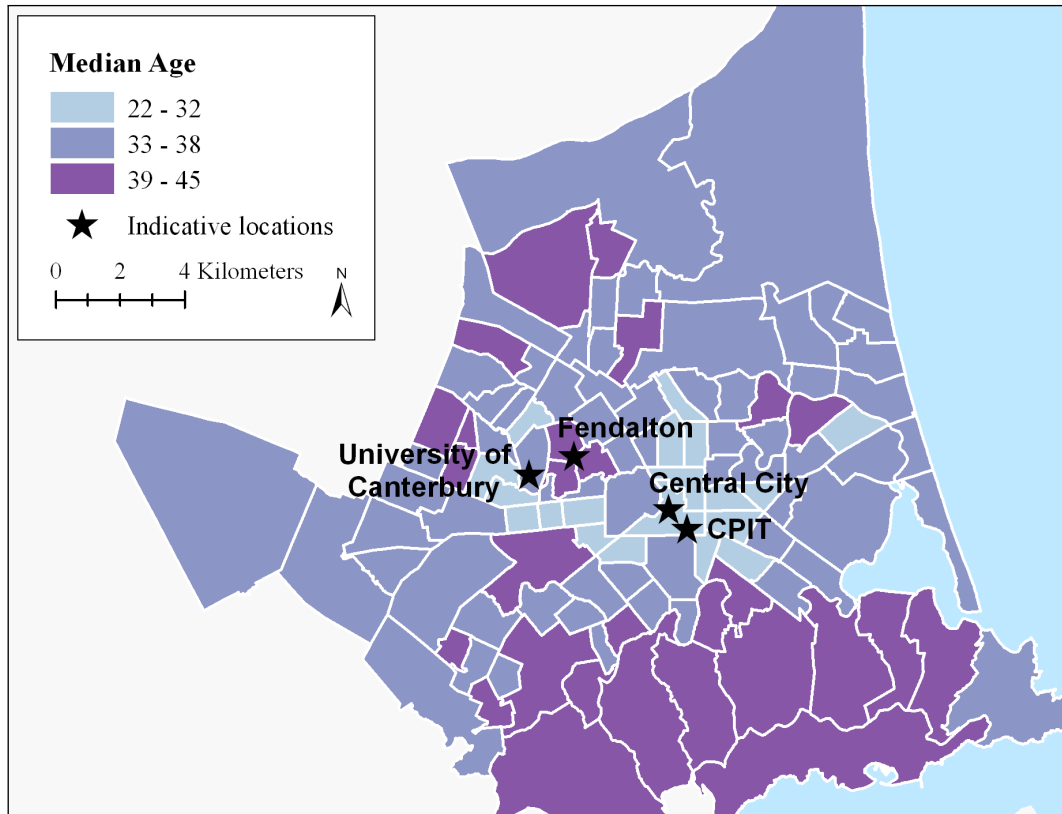
**Figure 6.4:** Christchurch topography and major roads



### 6.2.1 Study area inputs

#### 6.2.1.1 *Census data*

Census data used in the model was acquired from Statistics New Zealand, based upon the results of the 2006 census population survey. Results were obtained as a series of Excel spreadsheets and attached to census Area Unit boundaries, both attained from Statistics New Zealand. The age profile across the city, shown in figure 6.5 by the median age within each area, indicates a younger population within and near the central city, Christchurch Polytechnic Institute of Technology (CPIT) and University of Canterbury, and an older population typically on the fringes with the exception of Fendalton.

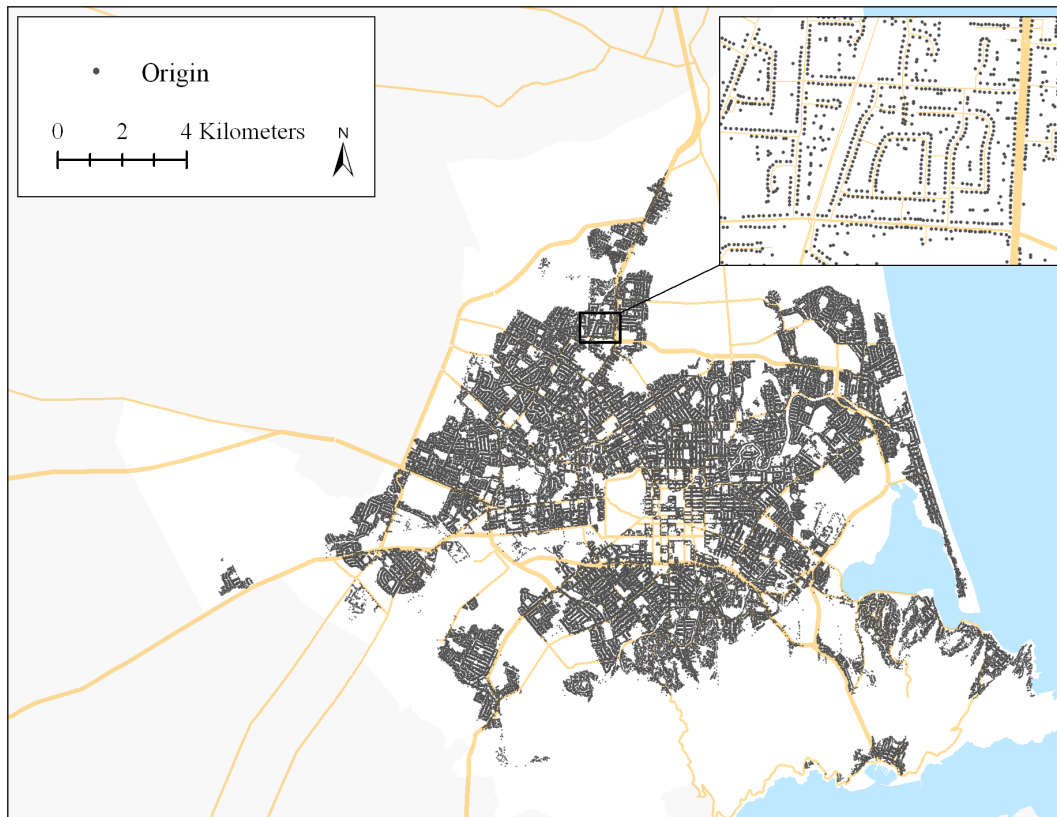


**Figure 6.5:** Distribution of age at census Area Unit level in Christchurch, key areas highlighted

#### 6.2.1.2 *Origins*

Each household within the study area is represented within the model as a point, the data used in the model is shown in figure 6.6. Other than the spatial location of

the origin, no attribute information is required. The data shows Christchurch as a relatively continuous residential area with two outlying towns: Lyttelton to the south and Templeton to the west, as shown in figure 6.2. There are also a number of fringe suburbs on the extreme edges of the city, including Southshore, Sumner, Halswell, Hornby and Belfast. The study does not consider origins lying outside the Christchurch City Council boundary. The dataset is derived from the Land Information New Zealand (LINZ) Core Record System, and was acquired from Abley Transportation Consultants Limited.

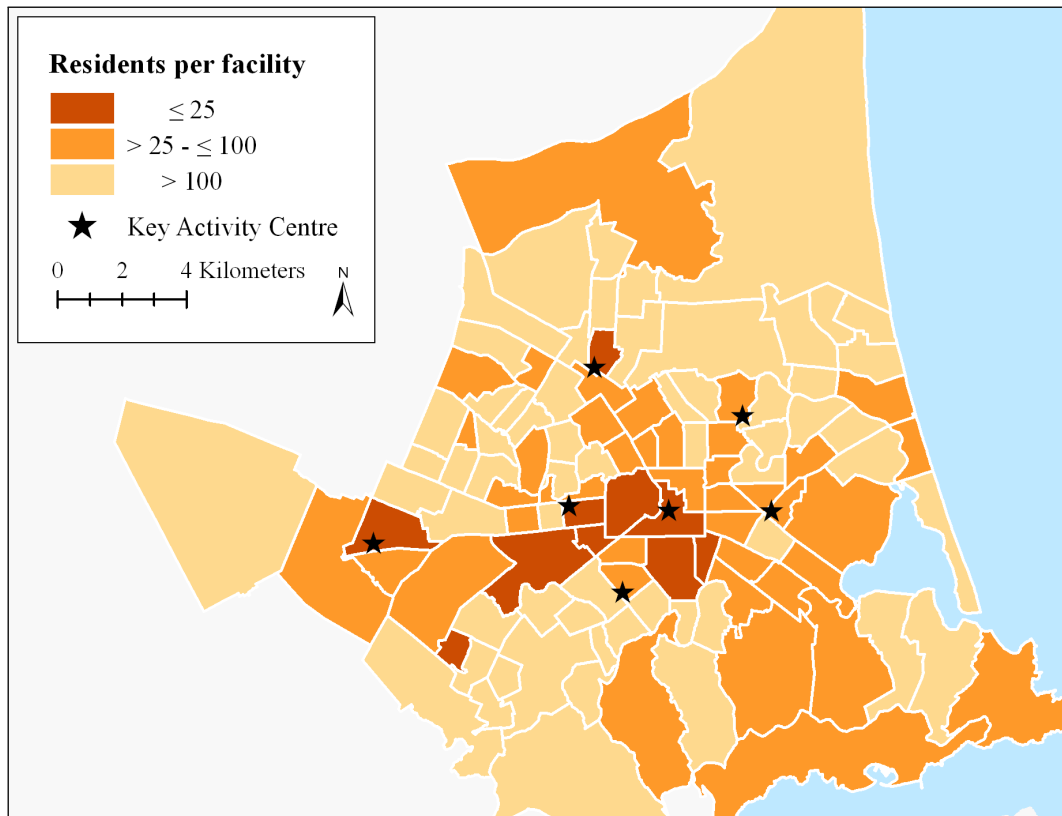


**Figure 6.6:** Origin points used within the Christchurch analysis; inset shows detail

### 6.2.1.3 Activity facilities

KACs are relatively evenly situated around Christchurch as shown in figure 6.3. KACs are not a direct input to the model, but do provide an indication of where activity facilities are clustered. The data used within the model is in the form of classified points, where each point represents one activity facility; if multiple activities can be performed at one location the point will be represented once for each activity, for example a cafe/book store would be represented as one point in *Shopping* and duplicated in *Social*

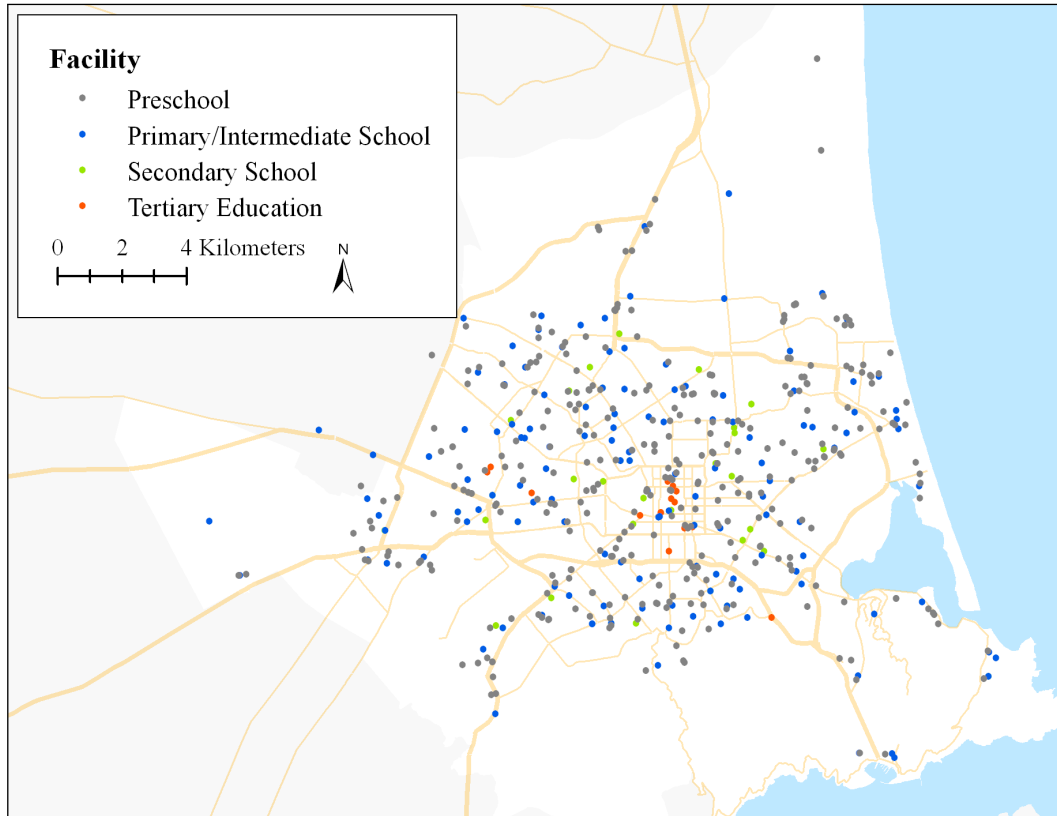
*visits*. For display, the facilities have been aggregated to the census Area Unit level, with education facilities excluded, and are shown as the number of residents per facility. Higher concentrations of facilities are observed within the central city and near KACs, as shown in figure 6.7.



**Figure 6.7:** Density of non-education activity facilities in Christchurch at census Area Unit level

Education facilities, classified into the four types used within the model, indicate a relatively even geographic spread, with decreasing density for higher levels of education, shown in figure 6.8. The Preschool activity includes Playgroups, Play-centres, Learning Centres, Crèches, Kindergartens, Childcare Centres, Te Kohanga Reo and Preschools, which results in a high density of facilities. As with other facilities, if an education facility falls into multiple categories it will be represented once in each category, for example, a school that teaches primary thorough to high school aged children at the same location.

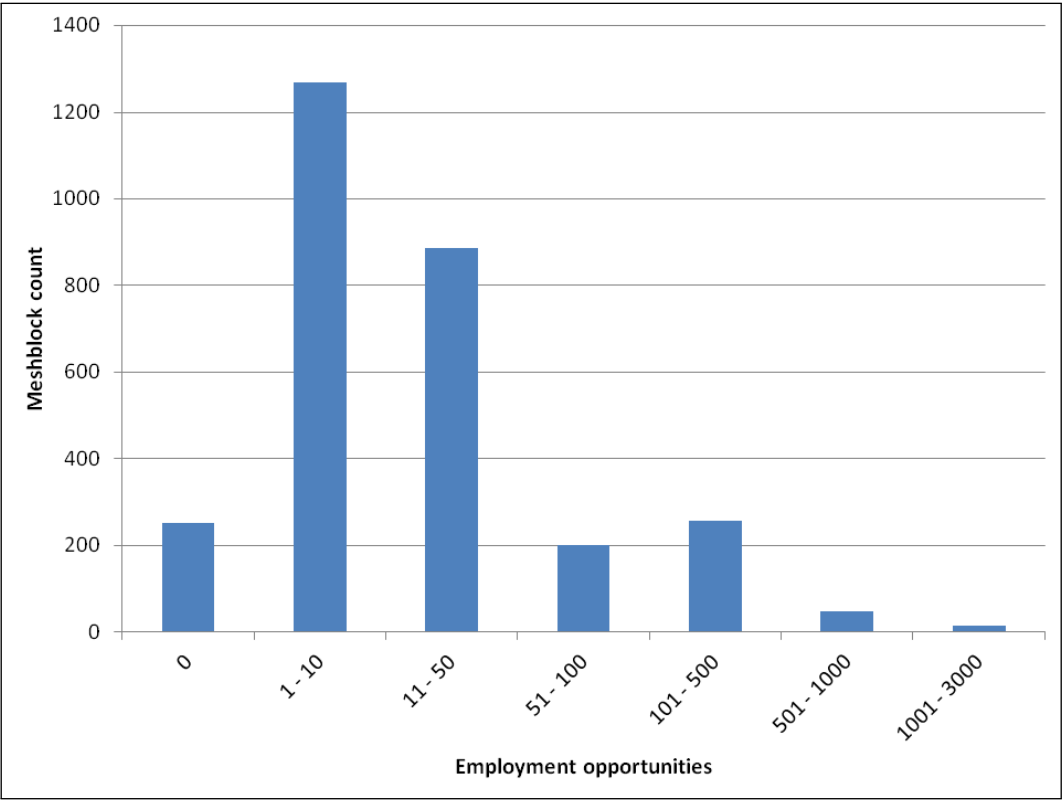
Activity facility data was derived from the *Everything from Zenbu.co.nz August 2011* community-contributed points of interest dataset, downloaded from <http://www.koordinates.com> and manually categorised into the appropriate classifications.



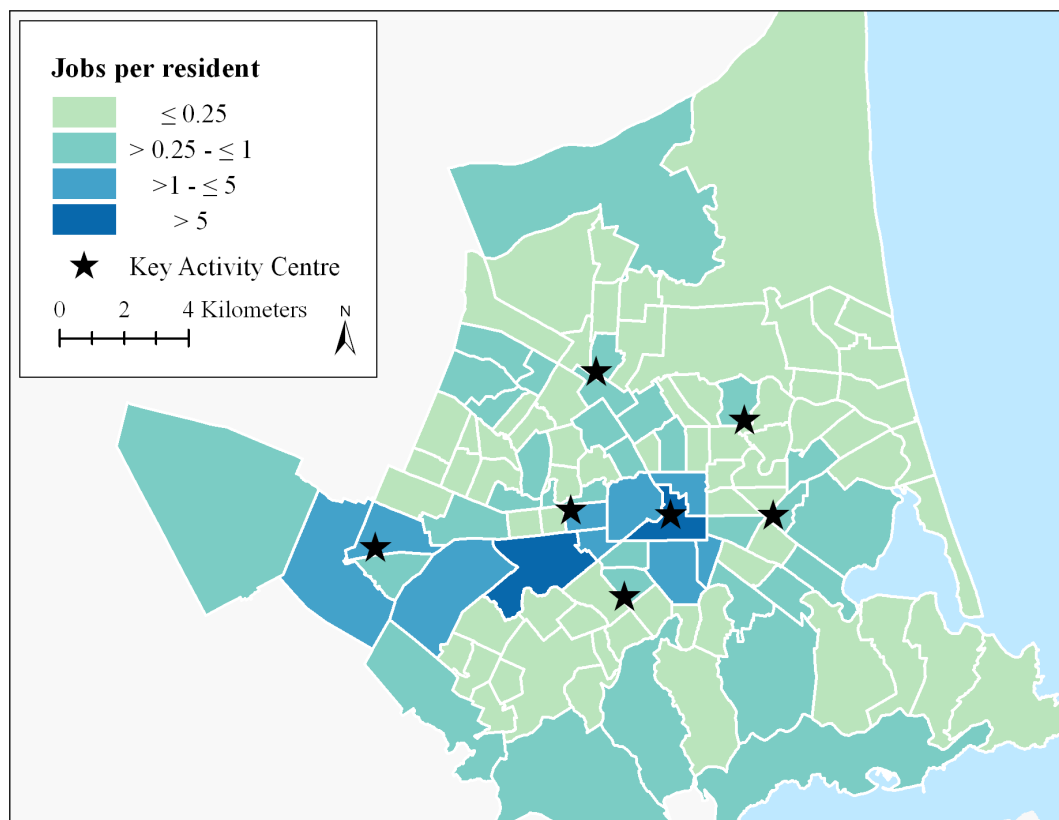
**Figure 6.8:** Spatial distribution of Christchurch education facilities

#### **6.2.1.4 *Employment facilities***

The model represents employment opportunities by proxy, through the number of potential employment opportunities per census Meshblock. This data was acquired from Statistics New Zealand as a Microsoft Excel spreadsheet and joined to the Meshblock boundary polygons file. Centroids were extracted to act as proxies for actual employment facilities. The dataset was acquired from Abley Transportation Consultants Limited. The number of employment opportunities per Meshblock ranges from zero to 2,379, with a mean value of 52, shown as a frequency histogram in figure 6.9. Employment opportunity density, aggregated to the level of census Area Units and shown as the number of jobs available per resident, is greatest in the central city, toward the south west of the city and near KACs, as shown in figure 6.10.



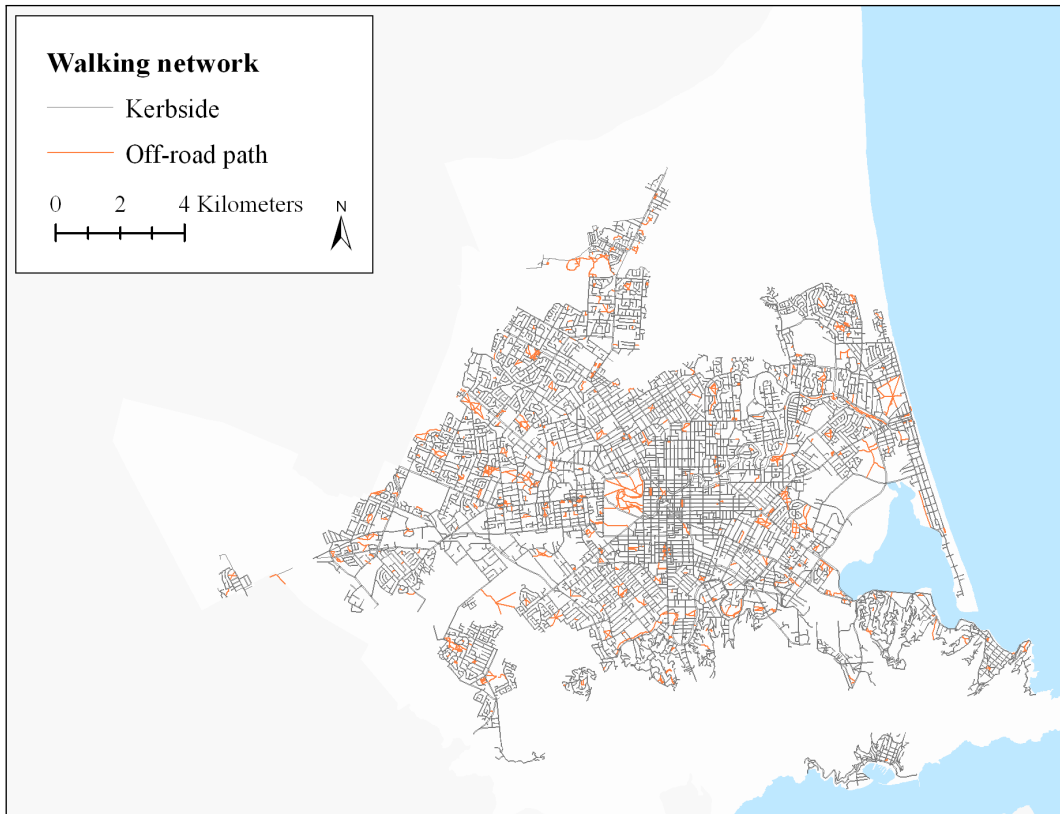
**Figure 6.9:** Frequency histogram of Christchurch employment opportunities at census Meshblock level



**Figure 6.10:** Density of Christchurch employment opportunities at census Area Unit level

### 6.2.1.5 Transport networks

The walking network represents roadside footpaths and off-road paths around Christchurch; although not all roads are assumed to have footpaths, as can be seen by gaps within the network in figure 6.11. A detail view showing footpaths, crossings and off-road paths is presented in figure 6.12. Link traversal time is calculated based upon an assumed speed of  $4.7\text{km/h}$  (Abley & Halden, 2012). Delays for crossing streets mid-block are determined by the road vehicle volume, which is derived from regional transport models, and at signalised intersections the delays are based upon the specific signal plan at the intersection. For the Christchurch network, these delays range from 2 to 120 seconds and are fully detailed in Abley and Halden (2012). The walking network was developed by, and acquired from, Abley Transportation Consultants Limited.



**Figure 6.11:** Christchurch walking network overview

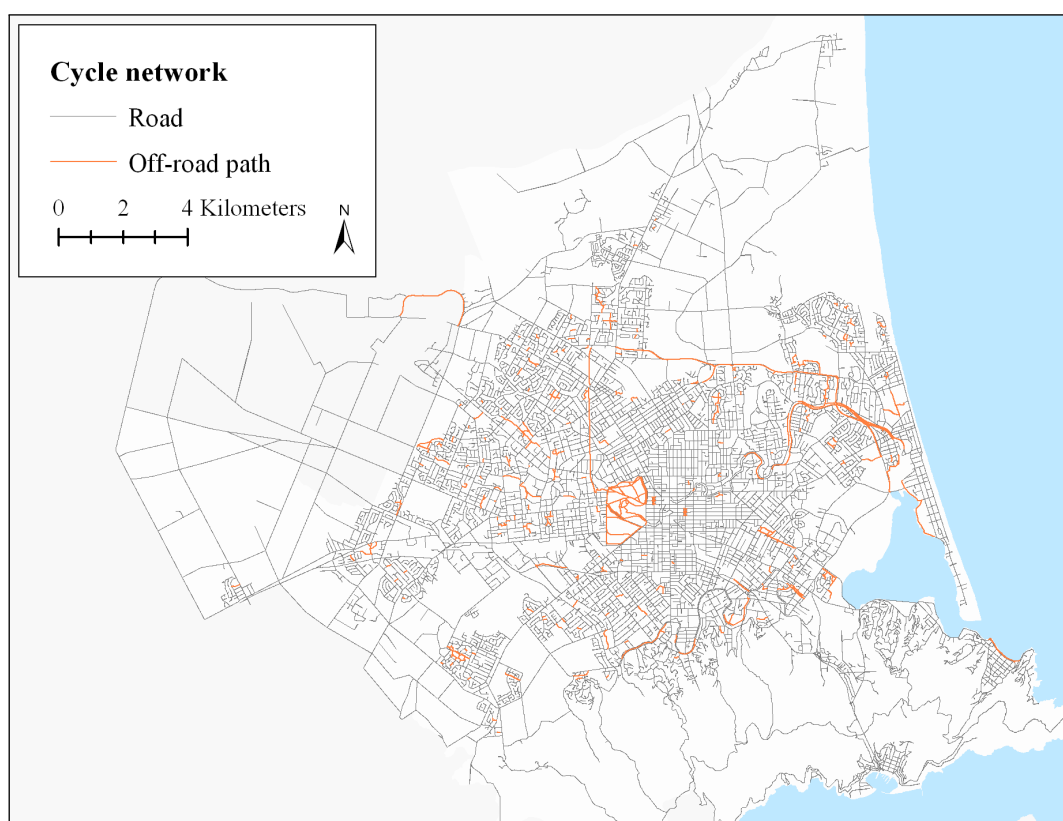




**Figure 6.12:** Christchurch walking network detail

The cycle network is based upon the road network, although off-road paths have also been included, as shown in figure 6.13. A detailed view showing off-road paths is presented in figure 6.14. Although it is possible to include intersection delays in this type of network, they have not been included in this particular network. Link traversal times were calculated upon an assumed speed throughout the network of  $15\text{km/h}$  (Abley & Halden, 2012). The cycle network was developed by, and acquired from, Abley Transportation Consultants Limited.



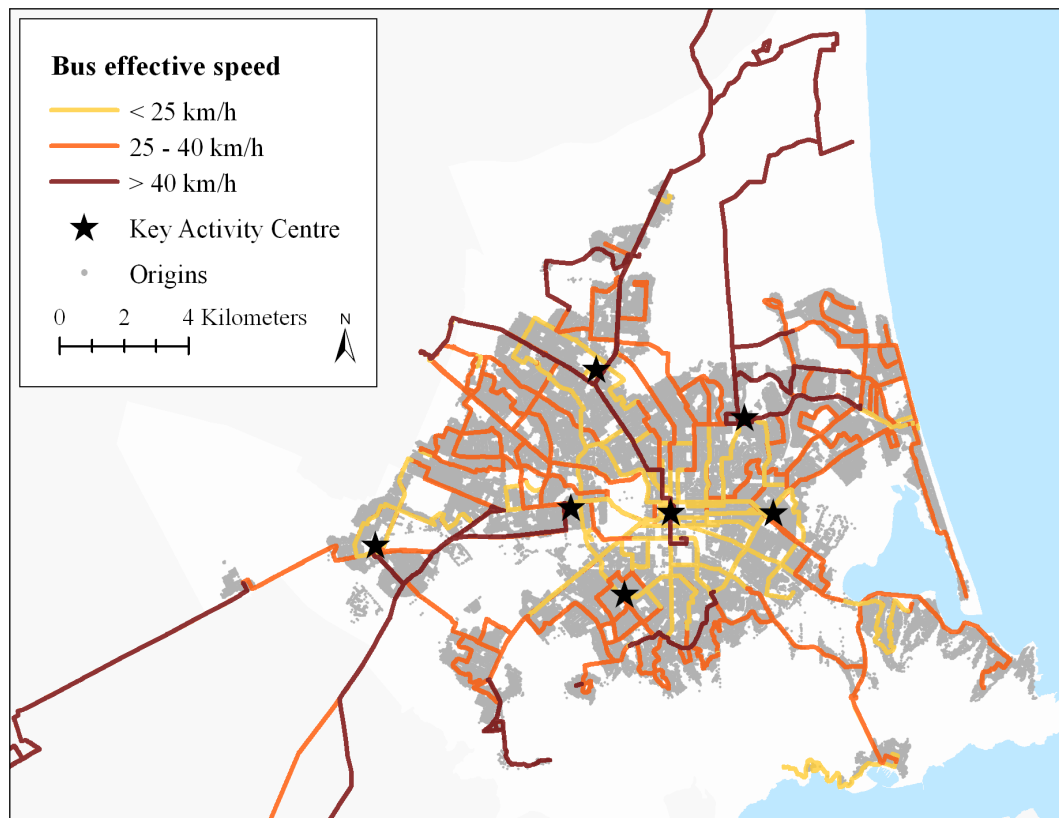


**Figure 6.13:** Christchurch cycle network overview



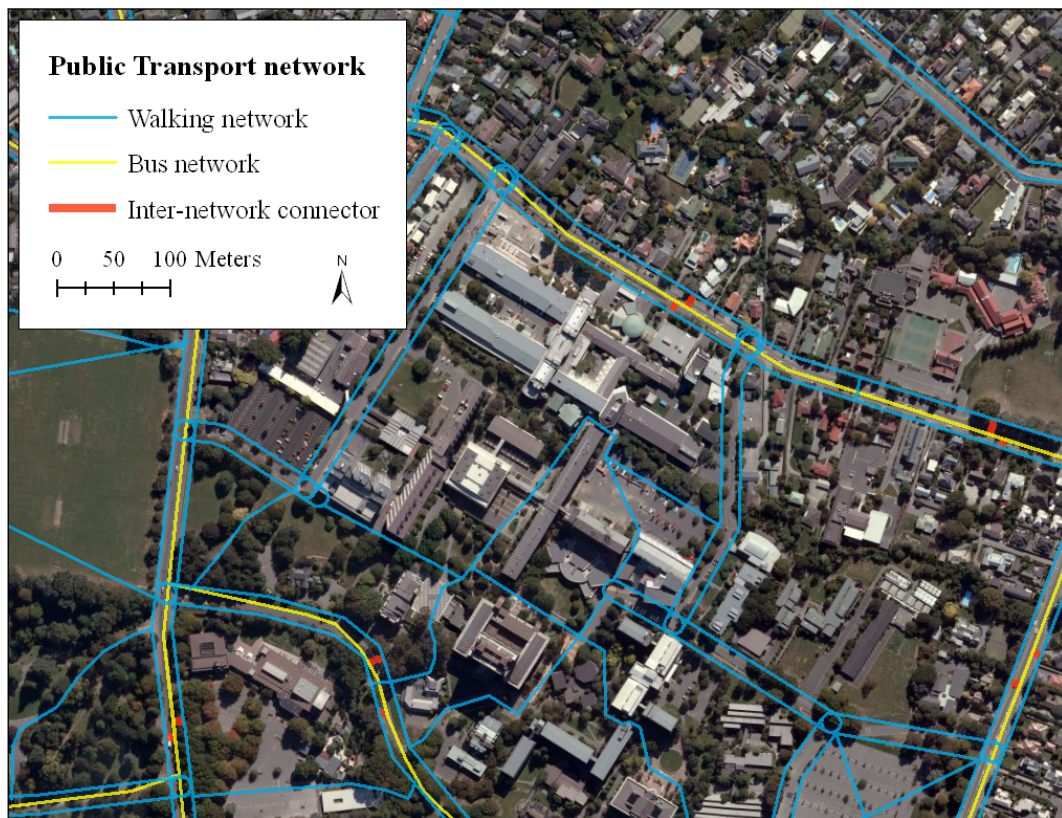
**Figure 6.14:** Christchurch cycle network detail

The public transport system in Christchurch consists only of buses. The network includes routes which pass through all the KACs and serve the majority of residential areas, as shown in figure 6.15. The effective speed at which buses travel is lower in areas of high residential density, which typically have higher levels of congestion and a greater density of intersections. Route maps for all routes prior to the 2010/2011 earthquakes are included in appendix A.1. The public transport network includes the walking network, to capture the walking legs that are usually required at either side of the public transport journey, as shown in figure 6.16 (Abley & Halden, 2012). Stops are represented as delays, which are equivalent to half the service frequency or 7.5 minutes, whichever is the lesser (Abley & Halden, 2012). This captures the effect that passengers will tend to use schedules for low frequency services while simply walking to the bus stop and waiting for high frequency services. In Christchurch only the *Orbiter* route operates as a high frequency service. The data shows that most households are close to a public transport route, although this does not guarantee that the service has an appropriate frequency. The areas of Sumner, Halswell and Belfast contain households which may be unable to access the network as routes are too far away. The public transport network was developed by, and acquired from, Abley Transportation Consultants Limited.



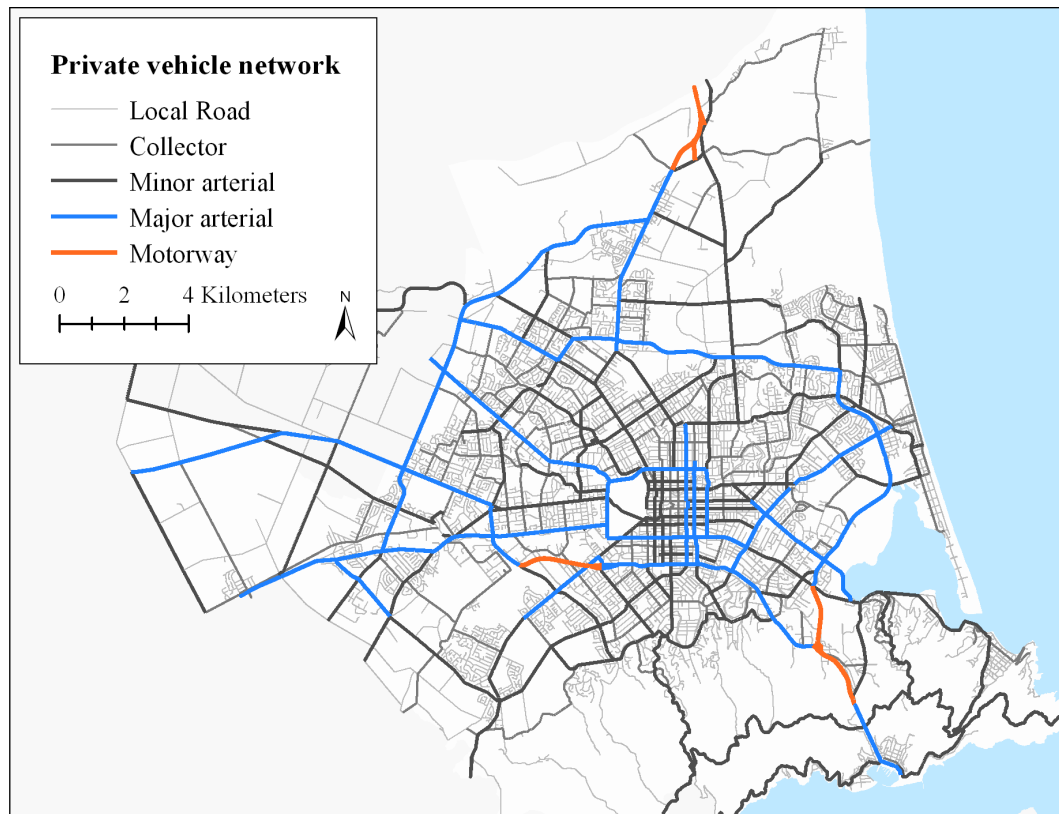
**Figure 6.15:** Christchurch public transport network overview: route outline and effective speeds





**Figure 6.16:** Christchurch public transport network detail: route specification and interface with walking network

The private vehicle network represents all roads accessible to private motor vehicles, and is shown in figure 6.17. Link traversal time is calculated based upon the expected effective speed of the segment, outlined for various road types in table 6.7. The network includes one way attributes, but not intersection delays. The public transport network was developed by, and acquired from, Abley Transportation Consultants Limited.



**Figure 6.17:** Christchurch private vehicle network overview

**Table 6.7:** Effective speed by road type used in the Christchurch private vehicle network (Abley & Halden, 2012)

Road type	Effective speed ( <i>km/h</i> )
Local road	30
Collector	30
Minor arterial	40
Major arterial	40
Motorway	70

### 6.2.2 Christchurch META analysis results

Results for the Christchurch case study are presented in this section. Specific areas of the city are identified, as necessary, by name as defined in figure 6.2. The results are divided into three main parts:

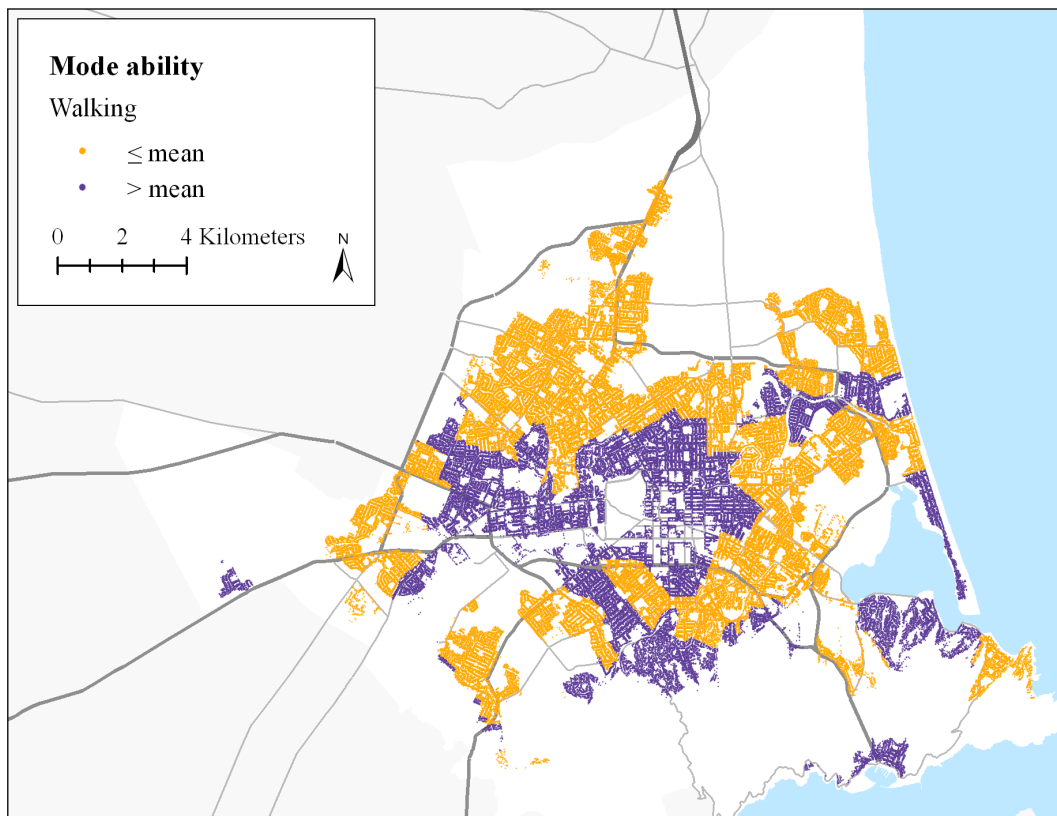
1. intermediate results, showing weighted mode abilities and total annual trips,
2. overall results, presenting the META household minimum transport energy consumption over the entire city, and
3. META mode and activity contributions, which detail the total energy consumption for travel by each mode and for travel to each activity.

#### 6.2.2.1 Mode ability results

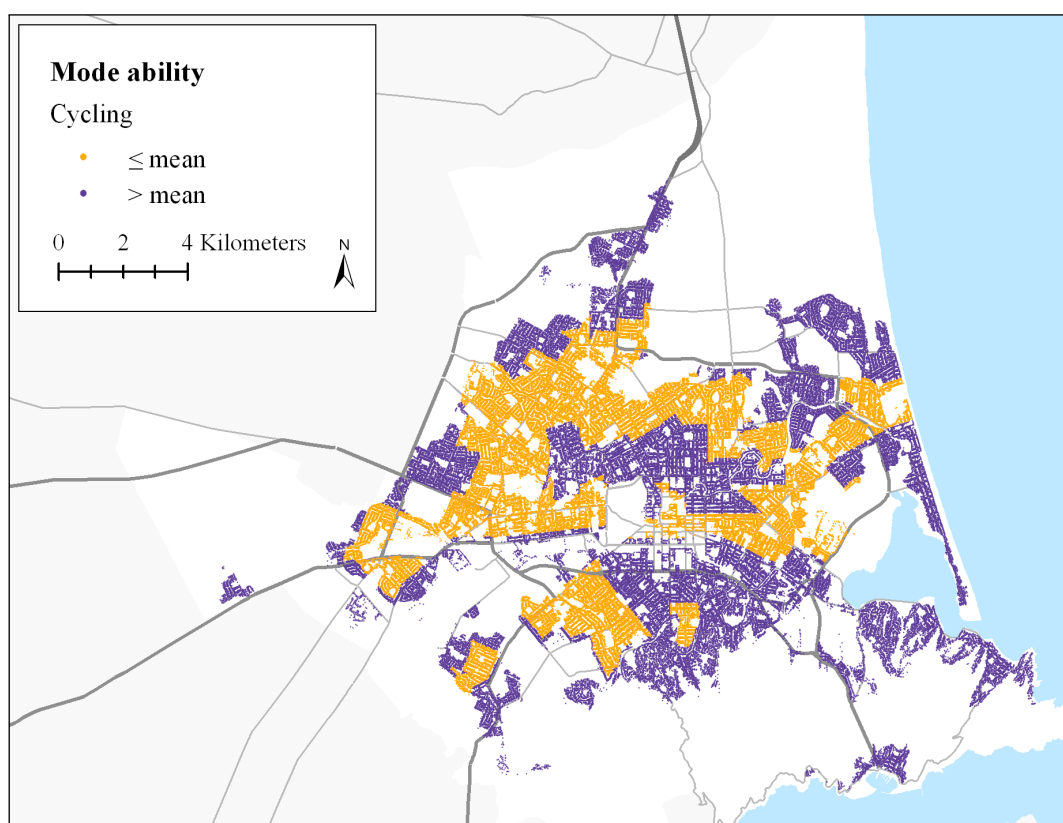
Mode abilities were weighted by census Area Unit demography, producing a spread of values which are outlined in table 6.8. The spatial distribution of weighted mode ability, displayed relative to the mean due to the low amount of variability, are shown for walking, cycling and public transport in figures 6.18, 6.19 and 6.20 respectively. The areas which are above and below the mean vary by each mode, but the variations are relatively small.

**Table 6.8:** Weighted mode abilities in Christchurch Area Units

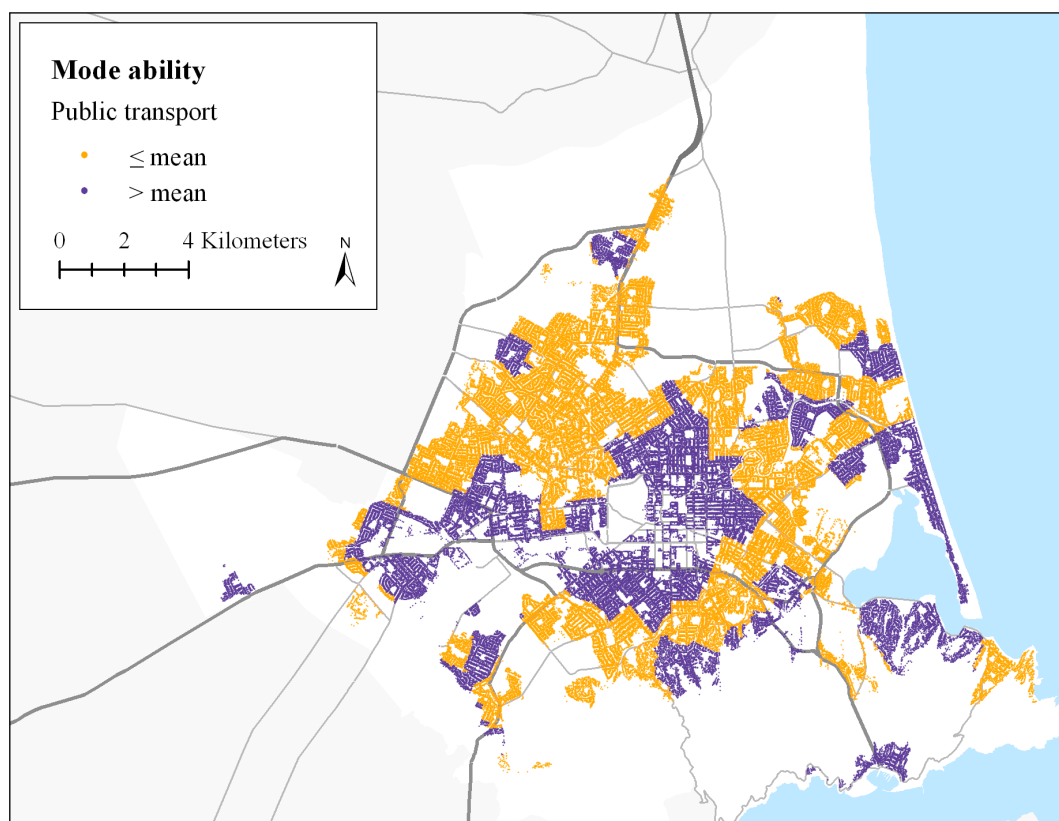
Age group	Mode ability (min)		
	Walk	Cycle	Public transport
Minimum	18.9	19.4	39.2
Mean	19.4	22.1	39.7
Maximum	20.1	23.1	40.4

**Figure 6.18:** Distribution of Christchurch walking mode ability





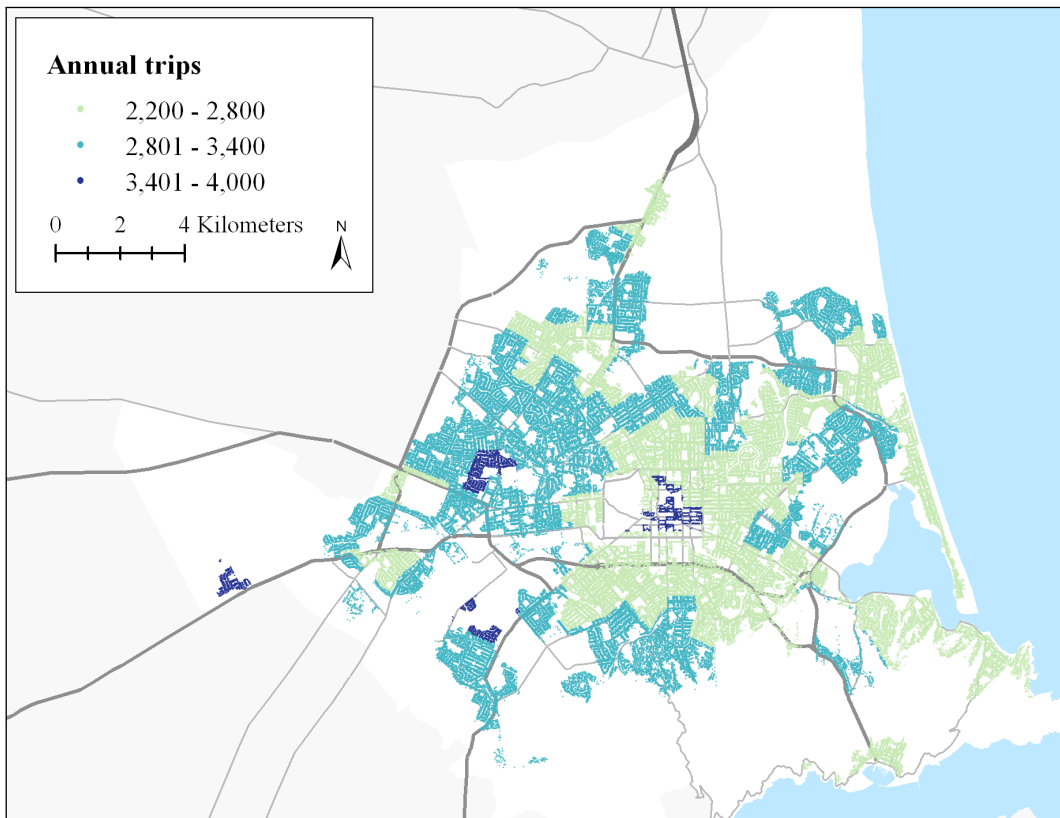
**Figure 6.19:** Distribution of Christchurch cycling mode ability



**Figure 6.20:** Distribution of Christchurch public transport mode ability

### 6.2.2.2 *Trip rate results*

The total annual number of trips for a household, which is dependent upon the resident population demography and household size, is shown in figure 6.21. It is the sum for all activities of the product of weighted frequency and trip chaining variables. There is significant variation in the annual number of trips per household, with some households making as few as 2,200 trips per year, while others make nearly twice that, at 4,000 annual trips. There is no obvious spatial pattern to the distribution of trip rates.

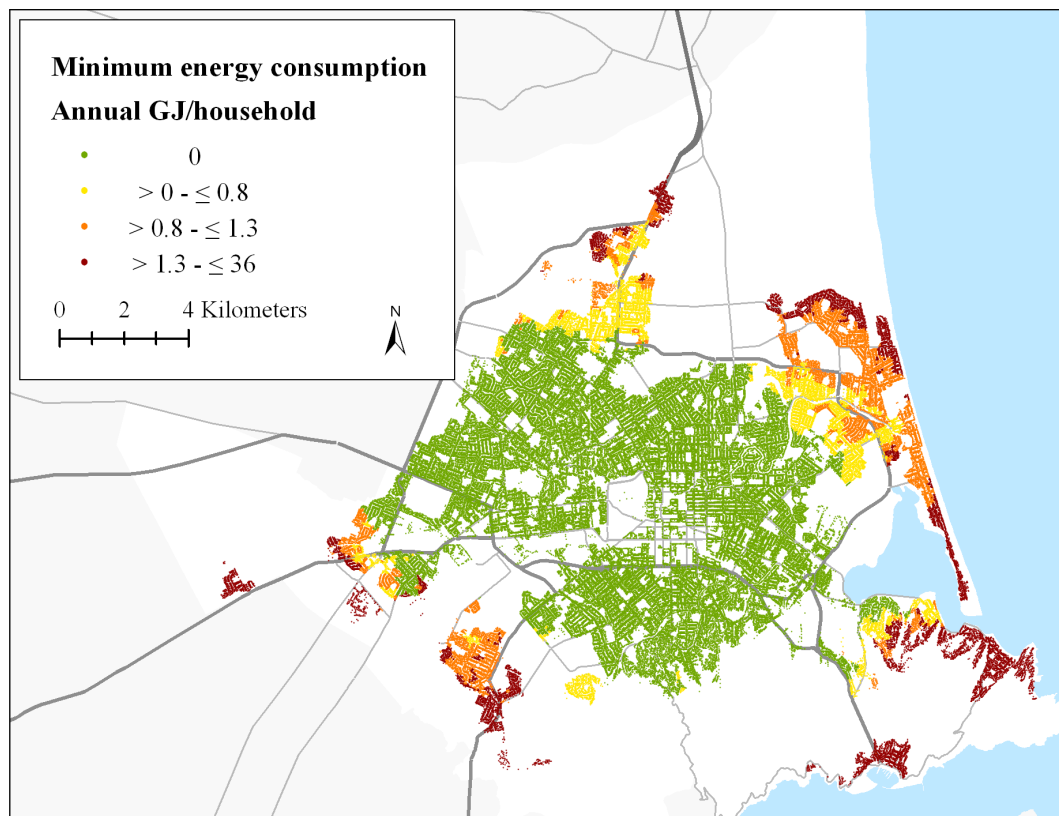


**Figure 6.21:** Distribution of Christchurch annual trip frequency

### 6.2.2.3 *META minimum energy results*

The calculated META minimum energy consumption within Christchurch is shown in figure 6.22 and summarised in table 6.9. The households shown in green lie in areas in which all META travel can be made by active modes, and thus have a minimum transport energy consumption of zero. Nearly 70% of households lie in areas that allow a zero minimum energy consumption. Yellow, orange and red households require greater amounts of energy to satisfy their transport requirements. For households with

a non-zero energy consumption the classification scheme is defined by equal percentiles, such that each group contains approximately the same number of households. Further away from the central city, areas require greater amounts of transport energy for residents to meet their activity needs. Most key outlying areas have a large proportion of households in the highest consumption category; while all households in the areas of Southshore, Sumner, Lyttelton and Templeton fall into the highest consumption category.



**Figure 6.22:** Distribution of Christchurch annual household META minimum transport energy consumption

**Table 6.9:** Annual Christchurch household META minimum transport energy consumption

Classification ( <i>Annual <math>\frac{GJ}{household}</math></i> )	Number of households	Percent of households
0	83,538	69.6
$> 0 - \leq 0.8$	11,862	9.9
$> 0.8 - \leq 1.3$	13,215	11.0
$> 1.3 - \leq 36$	11,442	9.5
<b>Total</b>	120,057	100.0

#### 6.2.2.4 META modal contributions

The META minimum energy value is the sum of travel by private vehicle and public transport, the following figures show the specific contribution of each of these modes to the total minimum energy value. Both are displayed with a classification scheme applying the same break values as defined for the overall minimum energy consumption shown in figure 6.22, but cut off at the highest value calculated for travel by the mode. Results are summarised in table 6.10. Households shown in grey lie in areas that do not require energy consumption by the specified mode. Travel modes for a trip are assigned by the minimum energy mode hierarchy, such that any trip for which public transport is viable is made by public transport, trips for which private vehicle is the only option are made by private vehicle.

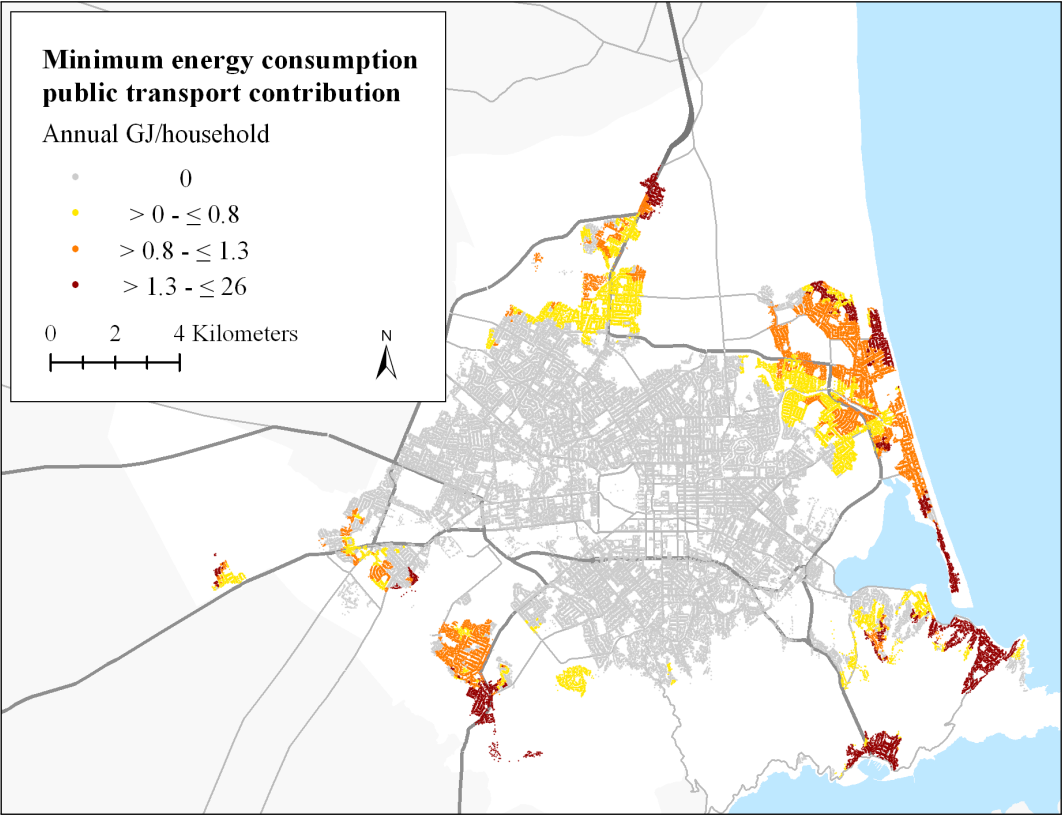
The contribution of public transport travel to META minimum energy consumption is shown in figure 6.23. As also shown in the overall META energy consumption figure, households near the centre of the city can travel without consuming any energy, including by public transport. The META results indicate nearly 27% of households lie in areas that require some travel by public transport. In general, households in areas further from the central city require greater amounts of energy. However, households in areas without access to the public transport network can be observed in Sumner, Halswell, Hornby, Belfast and Parklands as areas of zero public transport energy consumption lying beyond energy consuming areas. Areas with lower energy consumption that are located beyond those of medium or high consumption indicate where public transport may not be viable for all household activities, and can be

**Table 6.10:** Modal contributions to Christchurch annual household META minimum transport energy consumption

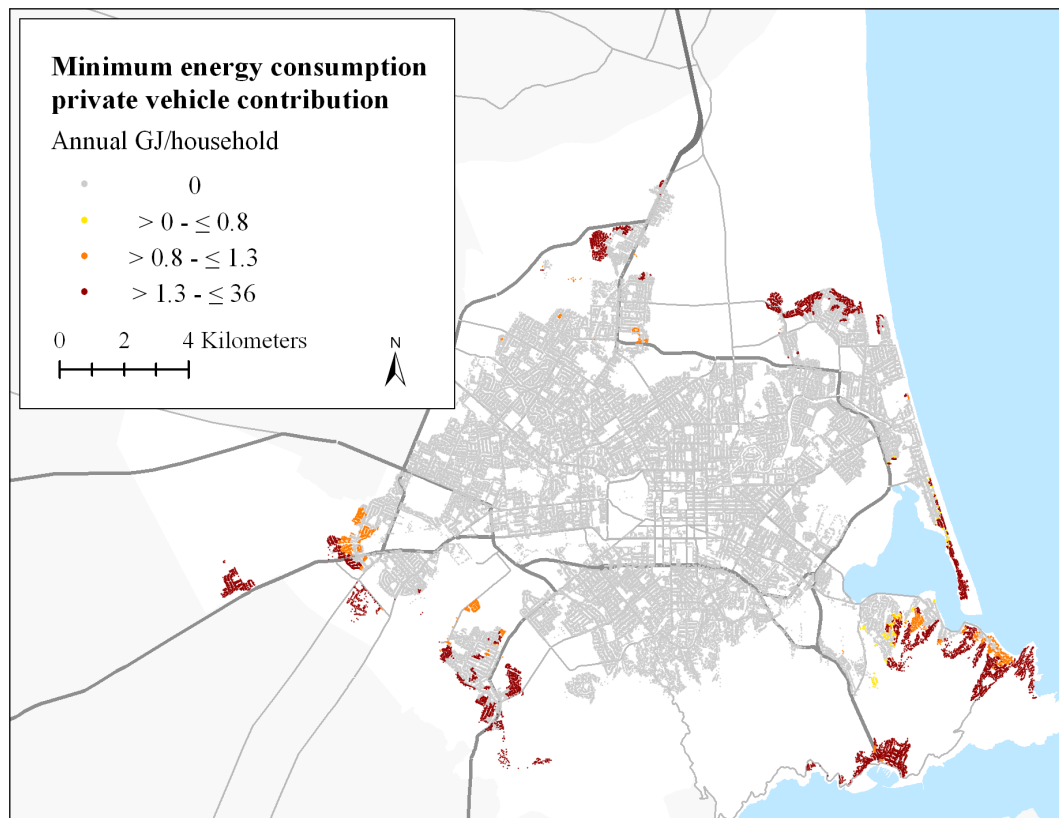
Mode	Classification ( <i>Annual <math>\frac{GJ}{household}</math></i> )	Number of households	Percent of households
Public transport	0	87,755	73.1
	$> 0 - \leq 0.8$	13,266	11.0
	$> 0.8 - \leq 1.3$	12,385	10.3
	$> 1.3 - \leq 26$	6,651	5.5
Private vehicle	0	110,480	92.0
	$> 0 - \leq 0.8$	284	0.2
	$> 0.8 - \leq 1.3$	1,646	1.4
	$> 1.3 - \leq 36$	7,647	6.4
<b>Total</b>		120,057	100.0

observed in Sumner, Hornby, Belfast and Parklands. The maximum META public transport energy consumption figure is  $26 \text{ GJ}/\text{household}$  per year.

The contribution of private vehicle travel to minimum energy consumption is shown in figure 6.24. As a result of the mode assignment hierarchy, this figure shows which households lie in areas lacking access to the public transport network or are unable to use public transport for the all of their trips. Eight percent of Christchurch households are in areas that require some travel by private vehicle, but most of these, six percent of all Christchurch households, fall into the highest consumption category. The areas of Southshore, Sumner, Lyttelton and Templeton predominantly feature households in the highest consumption category. The maximum META private vehicle energy consumption figure is  $36 \text{ GJ}/\text{household}$  per year.



**Figure 6.23:** Distribution of public transport contribution to Christchurch annual household META transport energy consumption



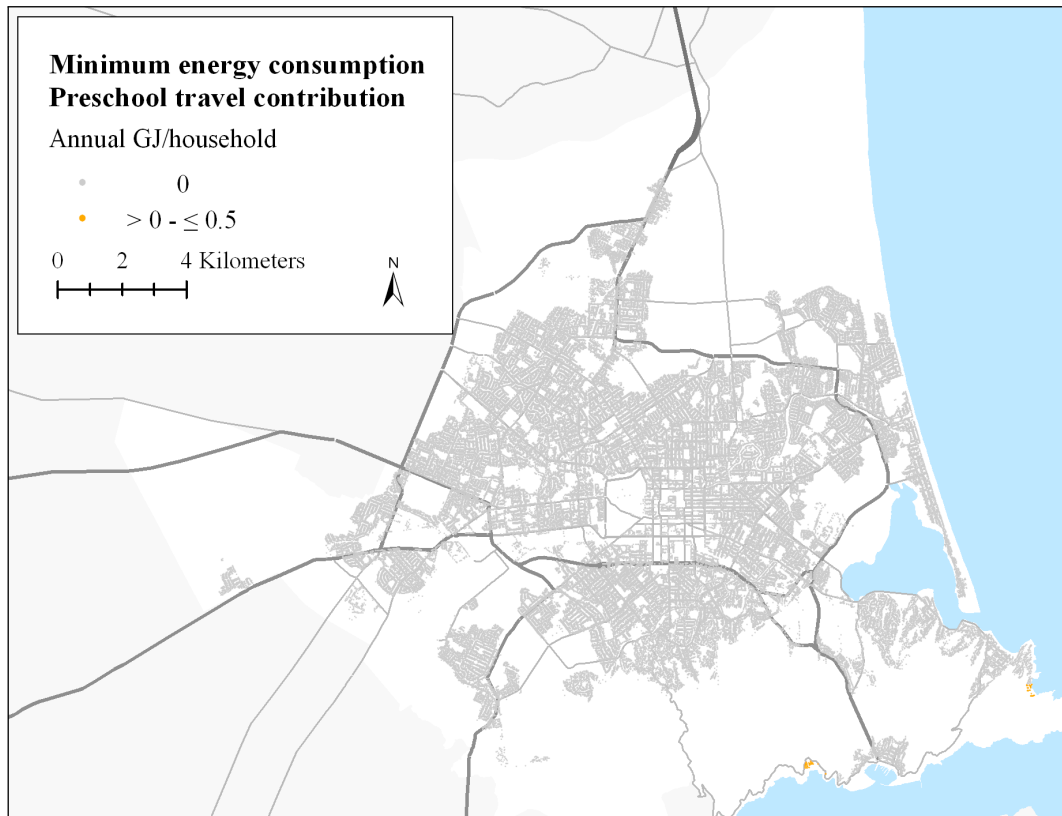
**Figure 6.24:** Distribution of private vehicle contribution to Christchurch annual household META transport energy consumption



### 6.2.2.5 META activity contributions

The META minimum energy value is the sum of annual travel to each activity, the following figures show the specific contribution of each activity to the total minimum energy value. The figures are displayed with a consistent classification scheme applying the break values from the highest META minimum energy activity, *Shopping*, as shown in figure 6.31, but cut off at the highest value calculated for travel to the activity. Results are summarised in table 6.11. Households shown in grey do not consume energy in travelling to the specified activity.

Under the META assumptions less than one percent of households lie in areas requiring energy consumption to reach Preschool facilities. Households that do require travel for this activity typically lie in areas on the very fringes of the city near Sumner and Lyttelton, as shown in figure 6.25. The energy requirement in all areas of reaching this activity is less than half a Gigajoule per year ( $\frac{GJ}{year}$ ).



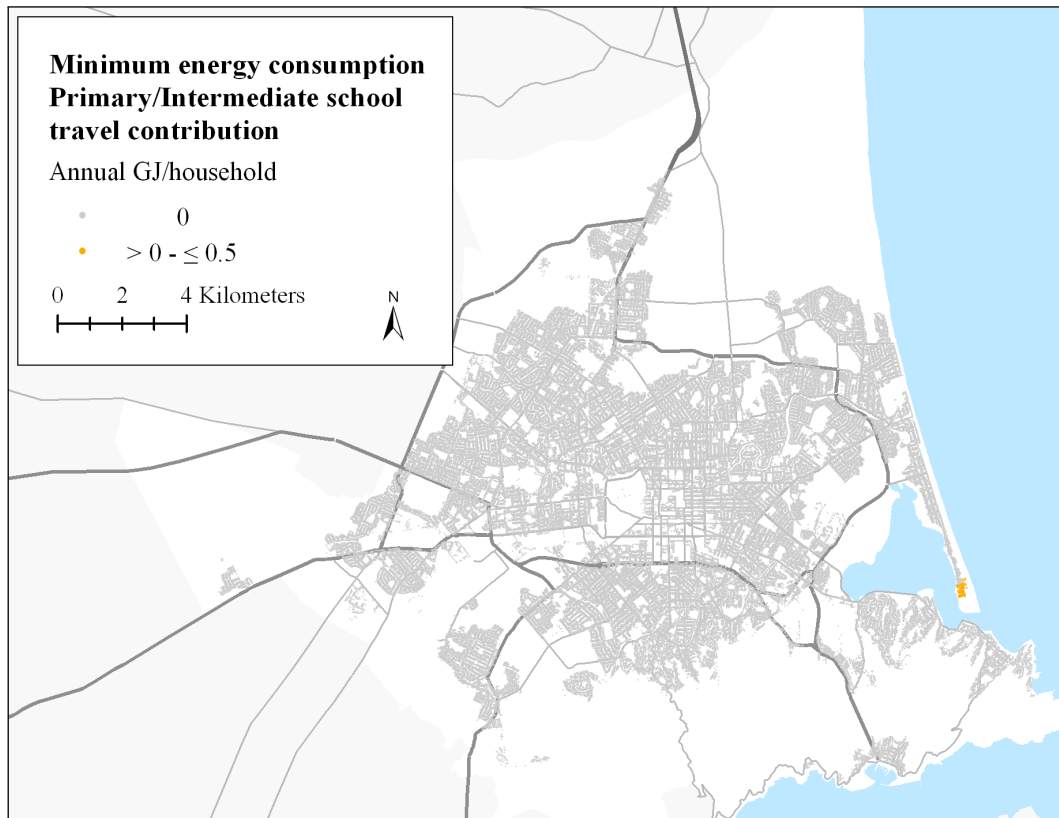
**Figure 6.25:** Distribution of Preschool travel contribution to Christchurch annual household META transport energy consumption

Less than one percent of households lie in areas requiring energy consumption to reach Primary/Intermediate school facilities, as shown in figure 6.26. All the households

**Table 6.11:** Activity contributions to Christchurch annual household META minimum transport energy consumption

Activity	Classification ( <i>Annual <math>\frac{GJ}{household}</math></i> )	Number of households	Percent of households
Preschool	0	119,976	99.9
	$> 0 - \leq 0.5$	81	0.1
Primary/Intermediate school	0	119,924	99.9
	$> 0 - \leq 0.5$	133	0.1
Secondary school	0	108,065	90.0
	$> 0 - \leq 1.7$	11,992	10.0
Tertiary education	0	84,337	70.2
	$> 0 - \leq 3$	35,720	29.8
Medical/dental	0	118,687	98.9
	$> 0 - \leq 0.6$	1,370	1.1
Personal business	0	115,727	96.4
	$> 0 - \leq 3$	3,986	3.3
	$> 3 - \leq 6$	336	0.3
	$> 6 - \leq 7$	8	$\approx 0.0$
Recreation	0	120,057	100.0
Shopping	0	114,966	95.8
	$> 0 - \leq 3$	1,720	1.4
	$> 3 - \leq 6$	1,575	1.3
	$> 6 - \leq 17$	1,796	1.5
Social visits	0	119,797	99.8
	$> 0 - \leq 3$	128	0.1
	$> 3 - \leq 6$	127	0.1
	$> 6 - \leq 7$	5	$\approx 0.0$
Employment	0	114,930	95.7
	$> 0 - \leq 3$	1,613	1.3
	$> 3 - \leq 6$	2,414	2.0
	$> 6 - \leq 11$	1,100	0.9
<b>Total</b>		120,057	100.0

that do are located in Southshore. The energy requirement in all areas of reaching this activity is less than half a Gigajoule per year.

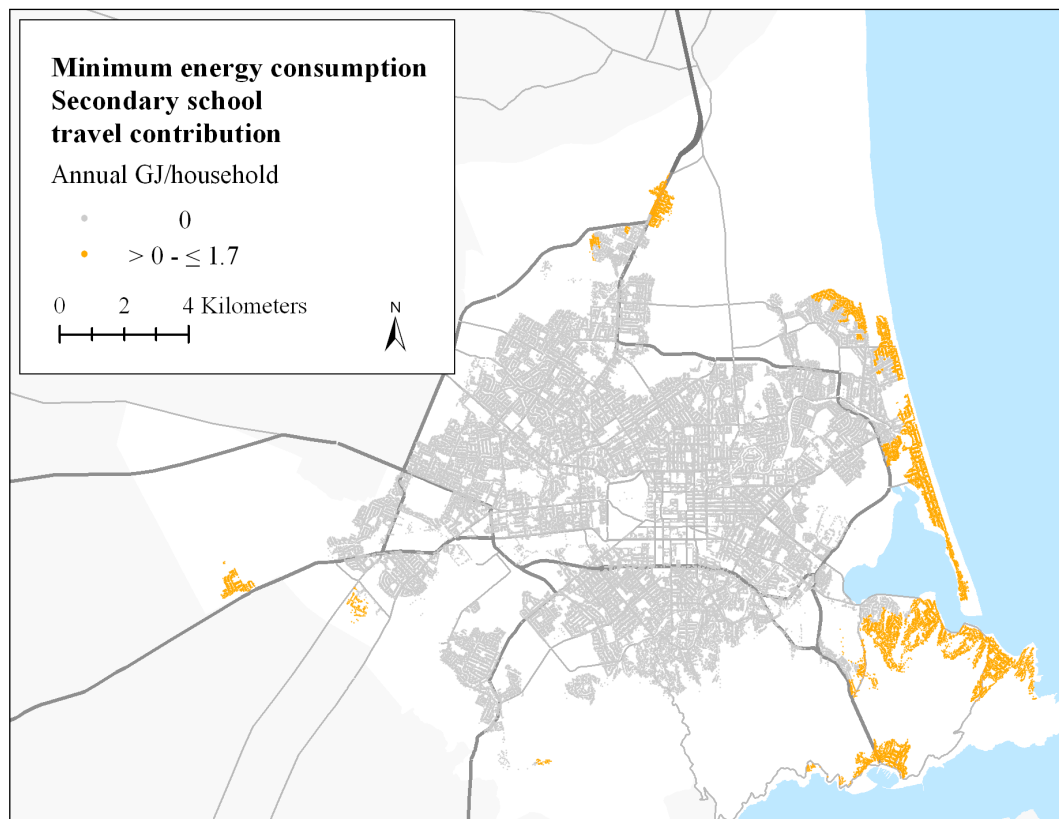


**Figure 6.26:** Distribution of Primary/Intermediate school travel contribution to Christchurch annual household META transport energy consumption

Ten percent of households lie in areas requiring some energy consumption in reaching Secondary school facilities, as shown in figure 6.27. A large proportion of the households in Southshore, Sumner, Lyttelton and Templeton require energy to travel to this activity. The energy requirement in all areas of reaching this activity is less than two Gigajoules per year.

Nearly 30% of households lie in areas requiring some energy consumption to reach Tertiary education facilities, as shown in figure 6.28. As these facilities are clustered in the centre and west of the city, energy is required for travel from areas in the north, east and south of the city. The energy requirement in all areas of reaching this activity is less than three Gigajoules per year.

Just over one percent of households lie in areas requiring energy consumption to reach Medical/Dental facilities, as shown in figure 6.29. A large proportion of the households in Lyttelton require energy consumption to reach this activity. The energy



**Figure 6.27:** Distribution of Secondary school travel contribution to Christchurch annual household META transport energy consumption

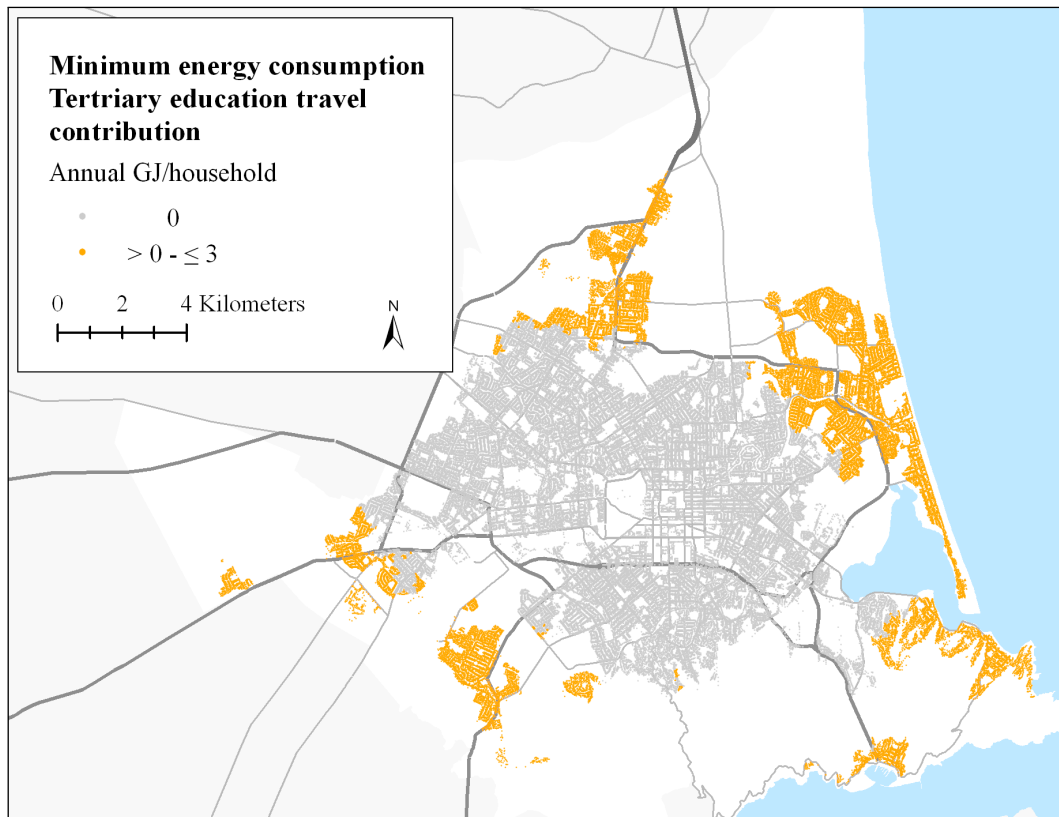
requirement for all households in reaching this activity is less than one Gigajoule per year.

Less than four percent of households lie in areas requiring energy consumption to reach Personal/Business facilities, as shown in figure 6.30. Areas requiring energy consumption to reach this activity are located on the fringes of the city, particularly Southshore, Sumner and Lyttelton. For most of the households requiring energy to reach this activity the annual requirement is less than three Gigajoules per year.

No areas in Christchurch require household transport energy consumption to reach Recreational facilities.

Over four percent of households lie in areas requiring energy consumption to reach Shopping facilities, as shown in figure 6.31. The areas of Southshore, Sumner and Lyttelton all require significant amounts of energy to reach this activity. The annual requirement in reaching this activity is as high as seventeen Gigajoules per year in some areas.

Less than one percent of households lie in areas requiring energy consumption to reach Social visit facilities, as shown in figure 6.32. Few areas require energy



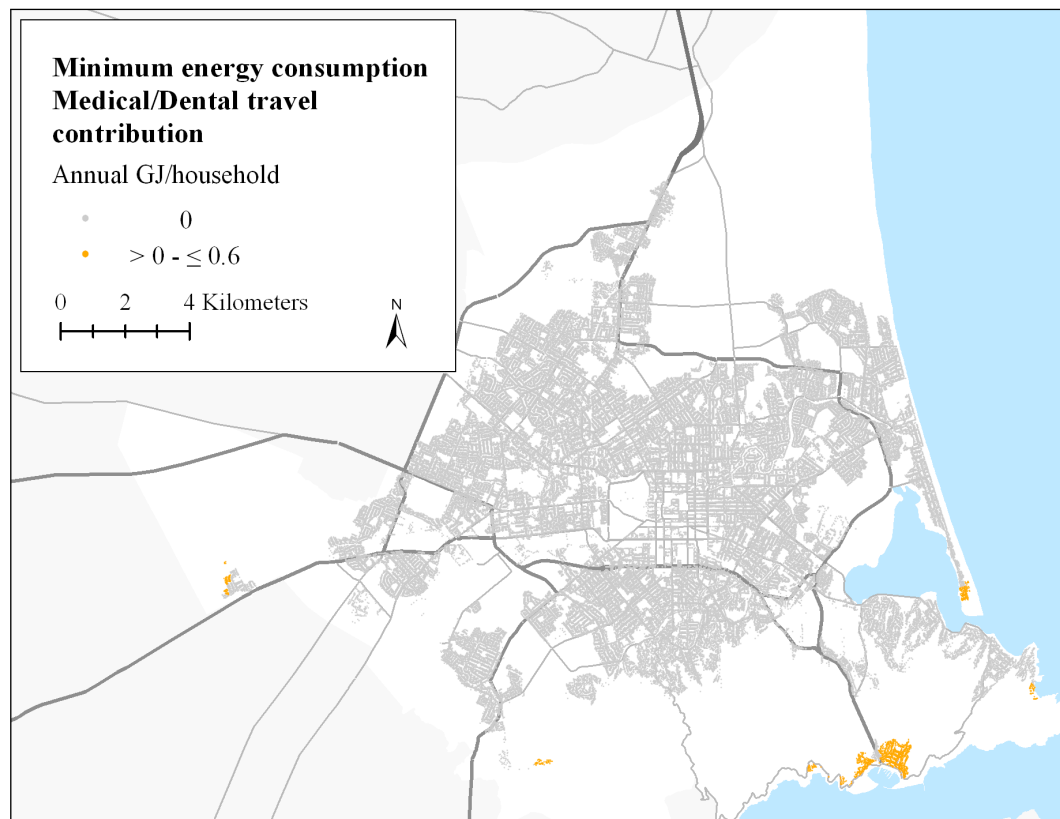
**Figure 6.28:** Distribution of Tertiary education travel contribution to Christchurch annual household META transport energy consumption

consumption to reach this activity, and are limited to Southshore, parts of Halswell and Templeton. The annual requirement in reaching this activity is as high as seven Gigajoules per year.

Over four percent of households lie in areas requiring energy consumption to reach Employment facilities, as shown in figure 6.33. Households that do require travel for this activity typically lie in areas to the south east of the city, including Southshore, Sumner and Lyttelton, as well as parts of Halswell. The annual requirement in reaching this activity is as high as eleven Gigajoules per year in some areas.

### 6.2.3 Summary of Christchurch results

Nearly 70% of households in Christchurch lie in areas that do not require transport energy consumption under the assumptions of the META model. This indicates that the majority of Christchurch households will be at low exposure to future energy supply constraints. However, areas on the fringes of the city, and outlying suburbs and towns, notably Southshore, Sumner, Lyttelton, Halswell, Templeton, Hornby, Belfast and

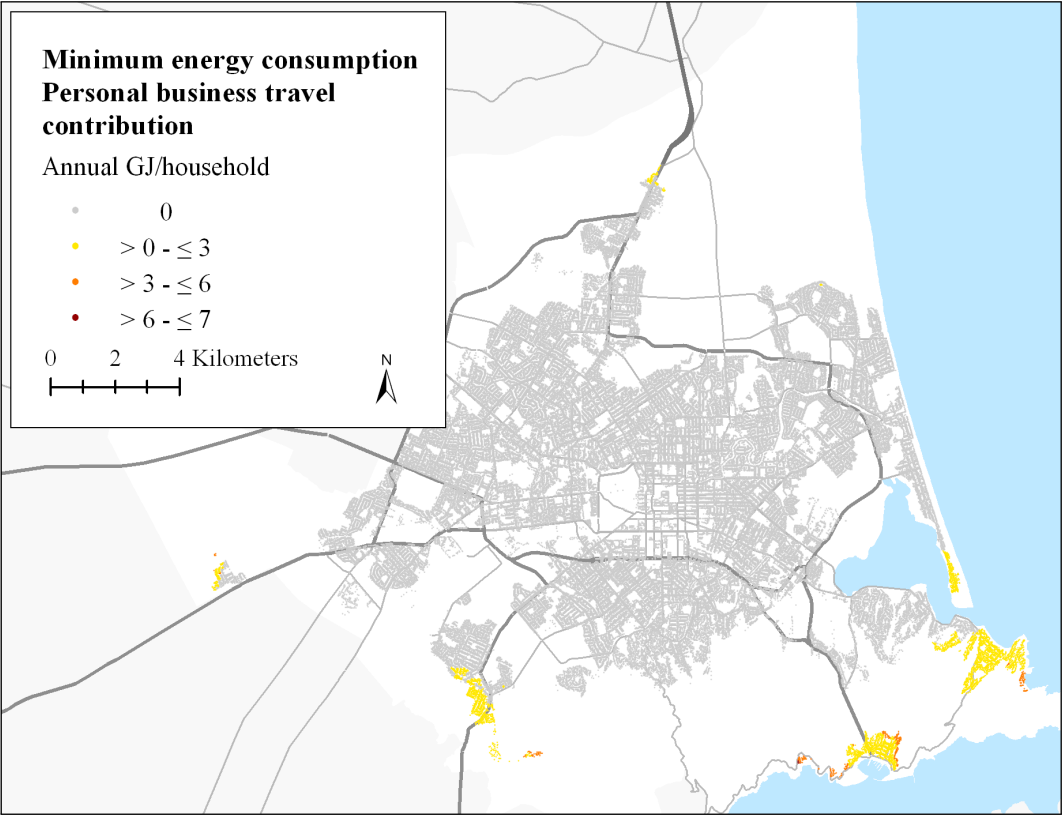


**Figure 6.29:** Distribution of Medical/Dental travel contribution to Christchurch annual household META transport energy consumption

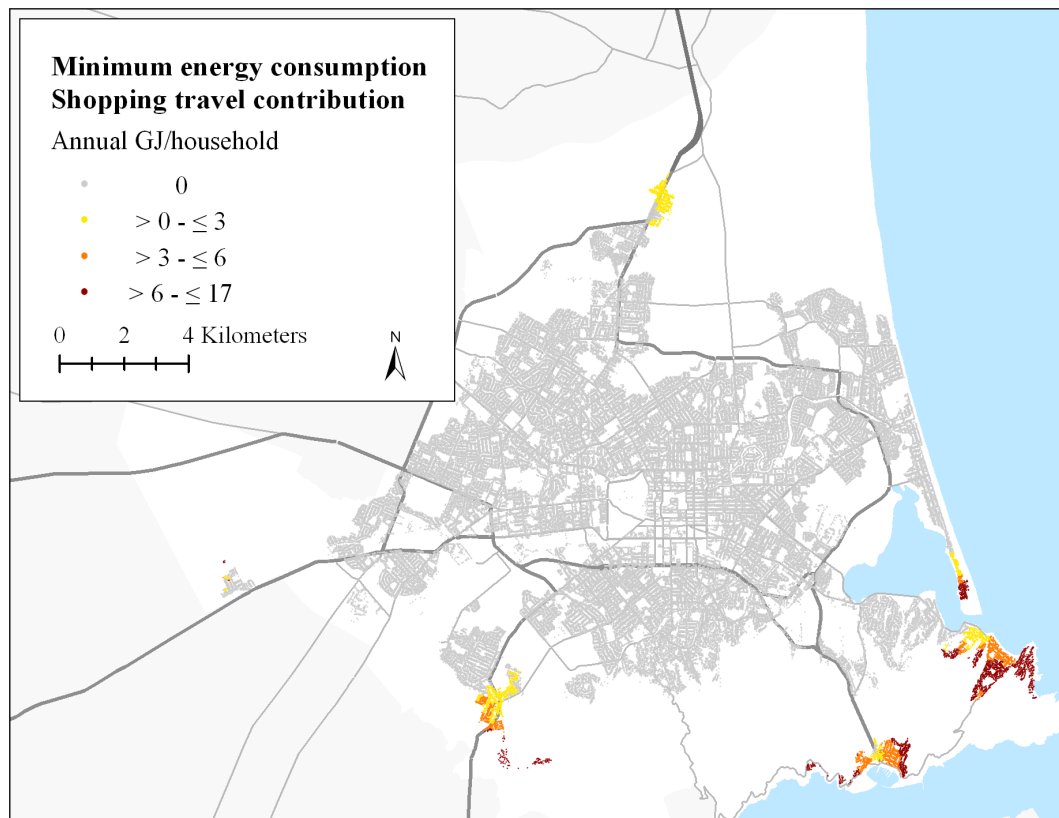
Parklands, require that residents consume significant amounts of transport energy in reaching their destinations. These areas severely limit the number and extent of adaptive responses open to residents.

Analysing the minimum energy results by mode highlights the mode limitations imposed by the urban form, particularly those areas lacking access to public transport, and areas in which public transport is not viable for all trips. Southshore, Sumner and Lyttelton, and parts of Halswell, Templeton, Hornby, Belfast and Parklands fall in the highest consumption categories for both private vehicle and public transport modes.

Viewing results by activity contribution to the META minimum energy requirement indicates the activity limitations of the urban form. Activities which are accessed less frequently contribute less to the total energy requirement, although they may still be important for certain demographic profiles. A few areas require energy consumption for almost all activities notably Southshore, Sumner, Lyttelton and parts of Halswell.

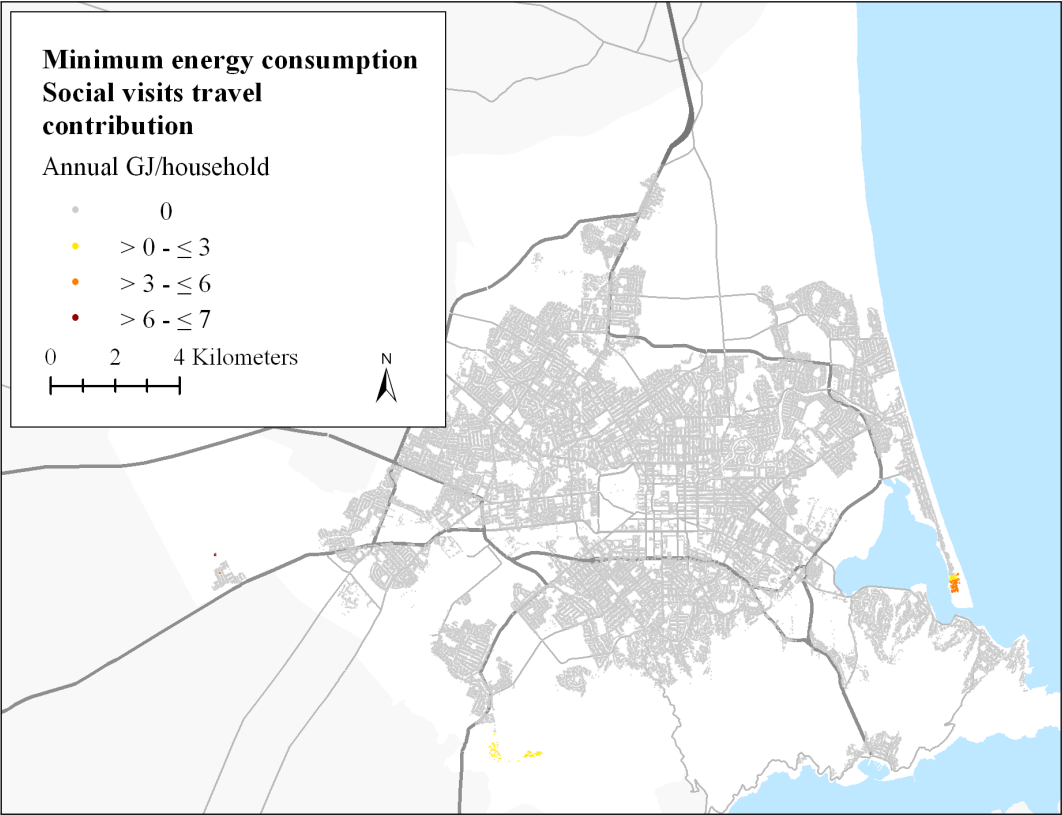


**Figure 6.30:** Distribution of Personal business travel contribution to Christchurch annual household META transport energy consumption

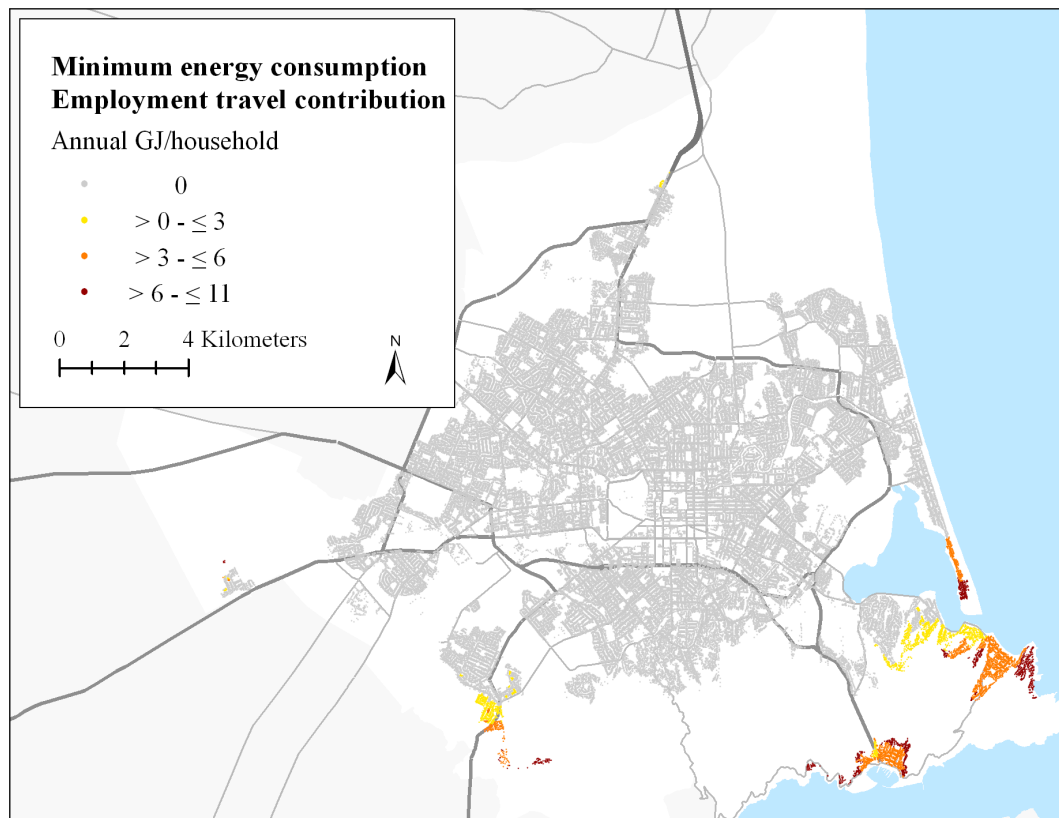


**Figure 6.31:** Distribution of Shopping travel contribution to Christchurch annual household META transport energy consumption





**Figure 6.32:** Distribution of Social visits travel contribution to Christchurch annual household META transport energy consumption

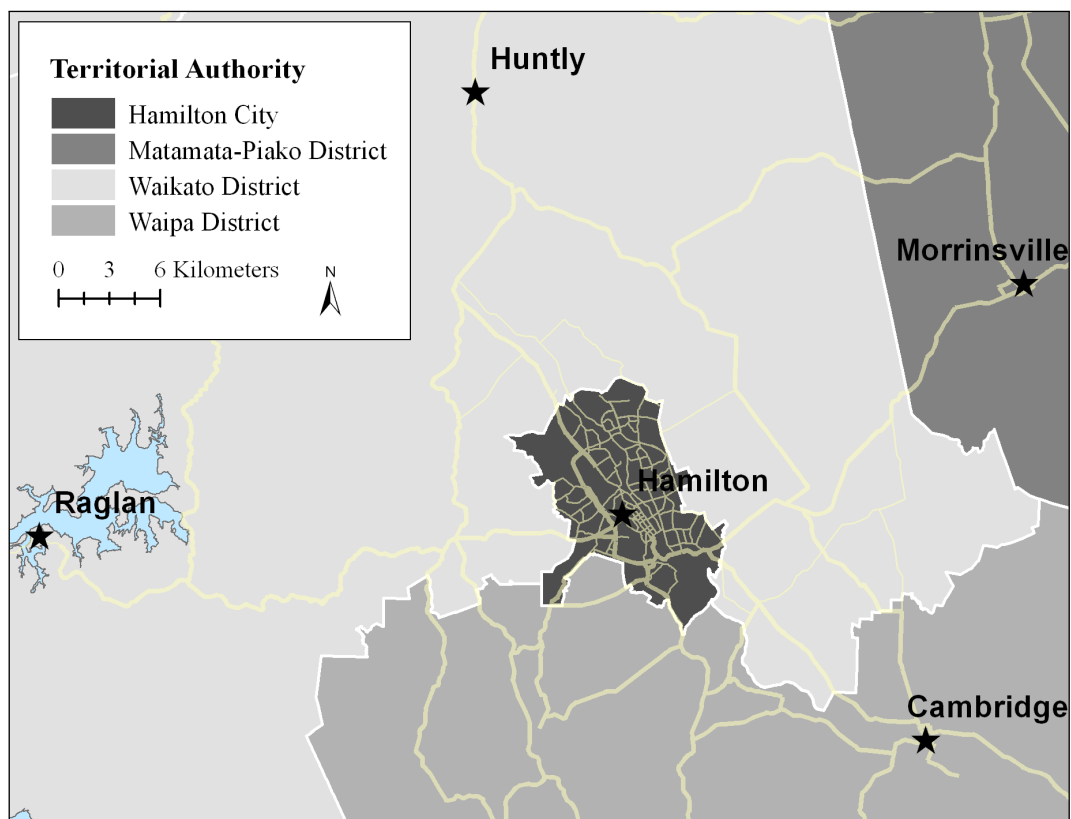


**Figure 6.33:** Distribution of Employment travel contribution to Christchurch annual household META transport energy consumption

## 6.3 Hamilton

Hamilton lies within the North Island region of Waikato and is the fourth most populous city in New Zealand. Hamilton city has a population of over 148,000 people in 53,000 households and a land area of 98 km<sup>2</sup>. The study area is somewhat smaller than the metropolitan area boundary and has an effective urban residential density of 13.6 persons per hectare.

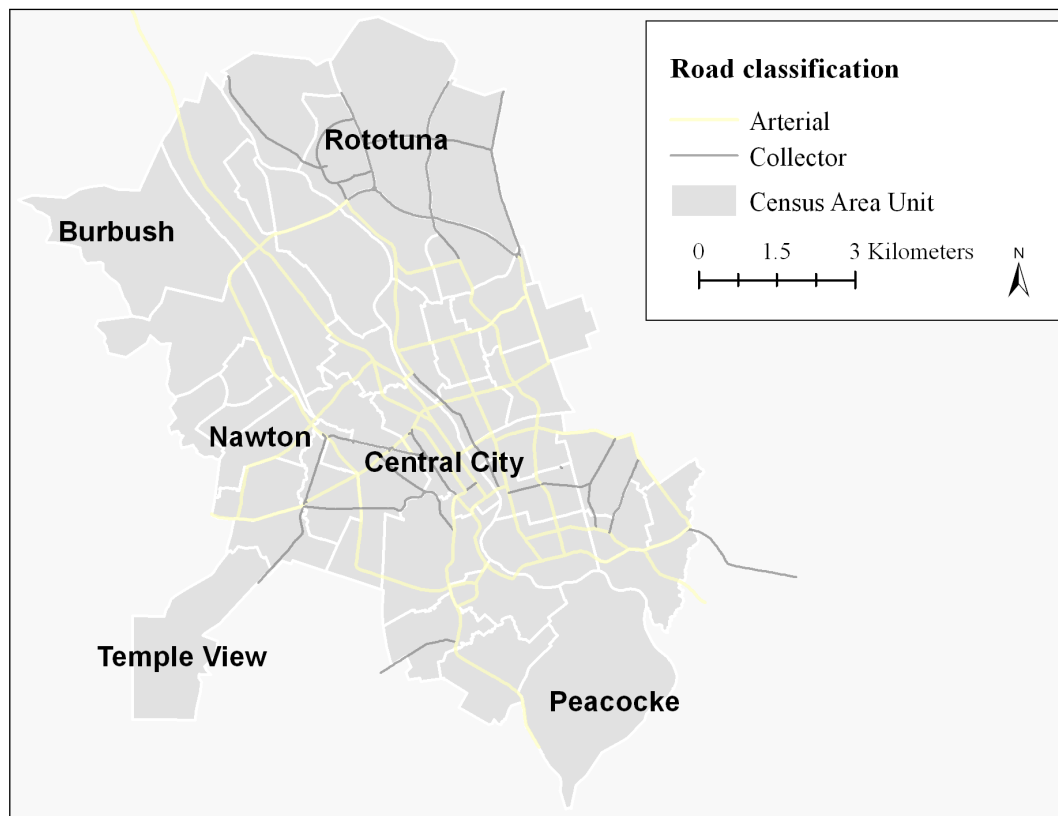
Hamilton is surrounded by a number of towns, and the city jurisdiction is bordered by the Waikato and Waipa districts, as shown in figure 6.34. Areas directly to the south east and south west of the city exhibit low density semi-rural residential land use patterns.



**Figure 6.34:** Hamilton region: communities proximate to Hamilton, Territorial Authority jurisdictions and major roads

Demographic data is utilised at the census Area Unit level to attain the highest resolution while minimising the number of confidential units. The boundaries of these units are shown in figure 6.35 along with key areas and major roads in Hamilton.

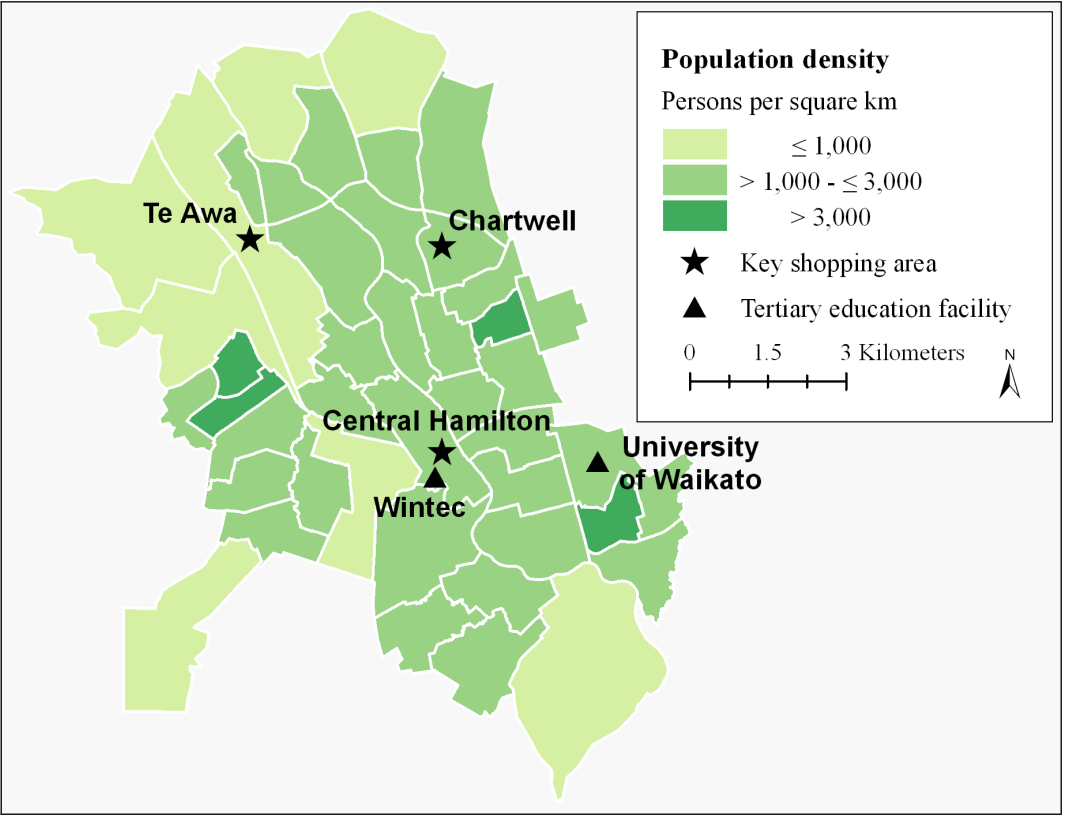
Most of the city area exhibits moderate levels of residential population density. Both the highest and the lowest density areas are situated near the urban fringe, as



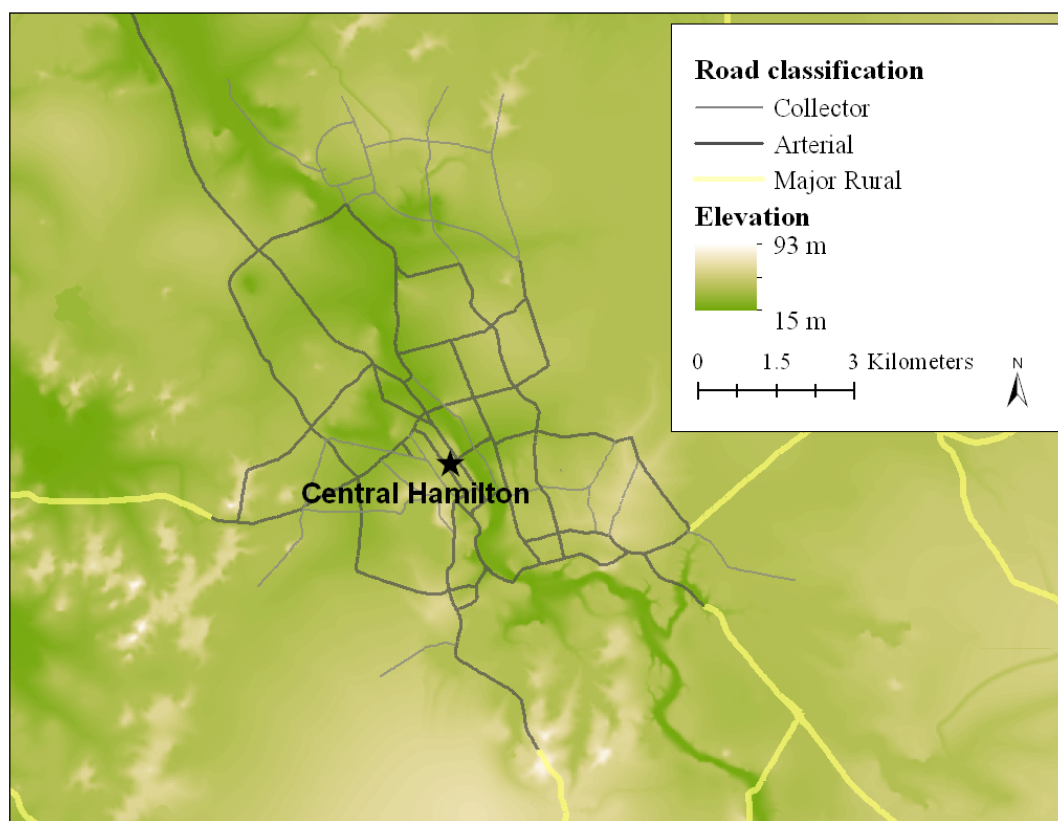
**Figure 6.35:** Hamilton city census Area Units, major roads and key outlying suburbs

shown in figure 6.36. The three key shopping areas in Hamilton provide an indication of where activity facilities are clustered, and are also shown in figure 6.36.

The Hamilton area exhibits a variation in elevation of nearly 90 metres, and there are a number of hills throughout the city, as shown in figure 6.37.



**Figure 6.36:** Hamilton city population density at census Area Unit level, key shopping areas and major Tertiary education facilities

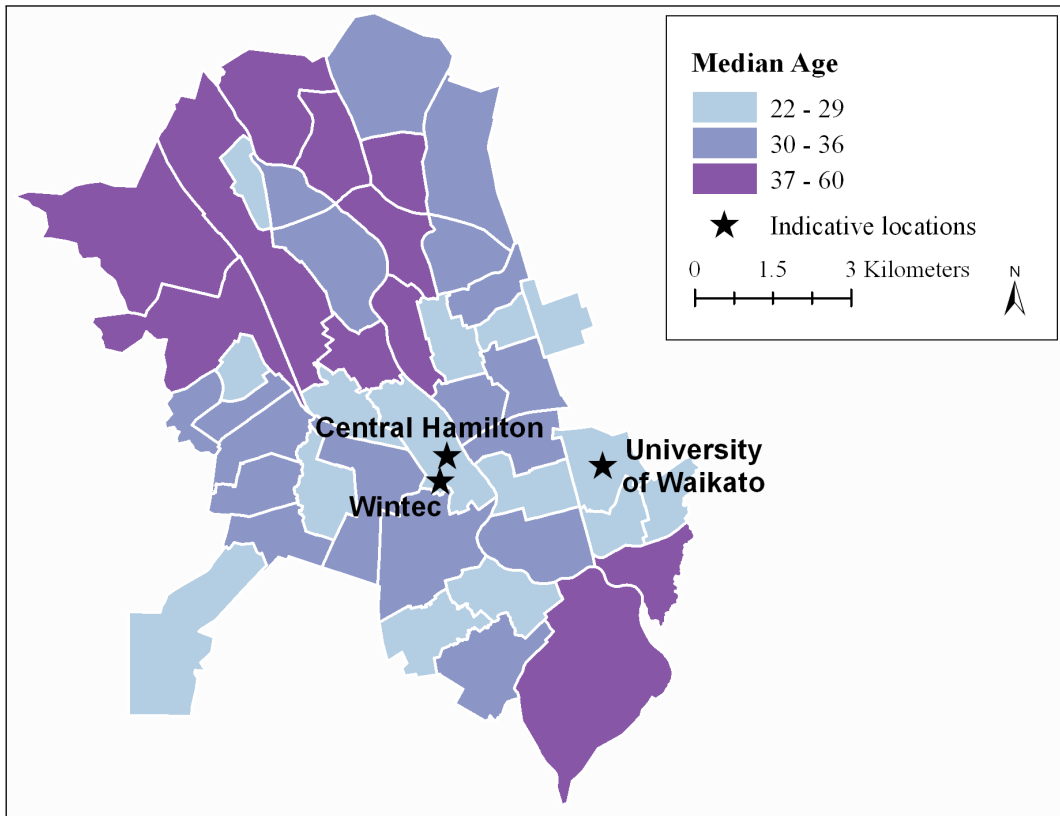


**Figure 6.37:** Hamilton topography and major roads

### 6.3.1 Study area inputs

#### 6.3.1.1 *Census data*

Census data used in the model was acquired from Statistics New Zealand, based upon the results of the 2006 census population survey. Results were obtained as a series of Excel spreadsheets and attached to census Area Unit boundaries, both attained from Statistics New Zealand. The age profile across the city, shown in figure 6.38 by the median age within each area, indicates a younger population within and near the central city, Waikato Institute of Technology (Wintec) and University of Waikato, and an older population typically towards the fringes.

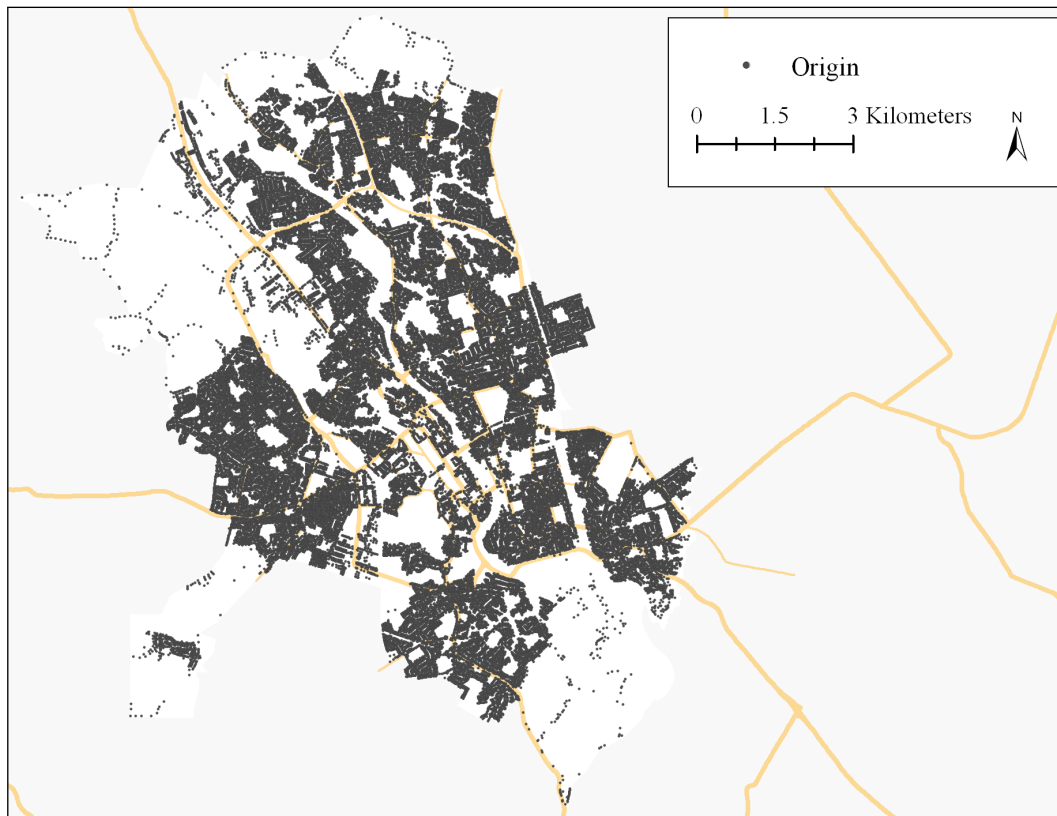


**Figure 6.38:** Distribution of age at census Area Unit level in Hamilton, key areas highlighted

#### 6.3.1.2 *Origins*

Each household within the study area is represented within the model as a point, the data used in the model is shown in figure 6.39. Other than the spatial location of the origin, no attribute information is required. The data shows Hamilton as a relatively

continuous residential area, with one outlying town, Temple View to the west of the city, and a number of lifestyle properties to the south of the city, in Peacocke, west near Temple View and in Burbush, and north, above Rototuna. The study does not consider origins lying outside the Hamilton City Council boundary. The dataset is derived from the Land Information New Zealand (LINZ) Core Record System, and was acquired from Abley Transportation Consultants Limited.

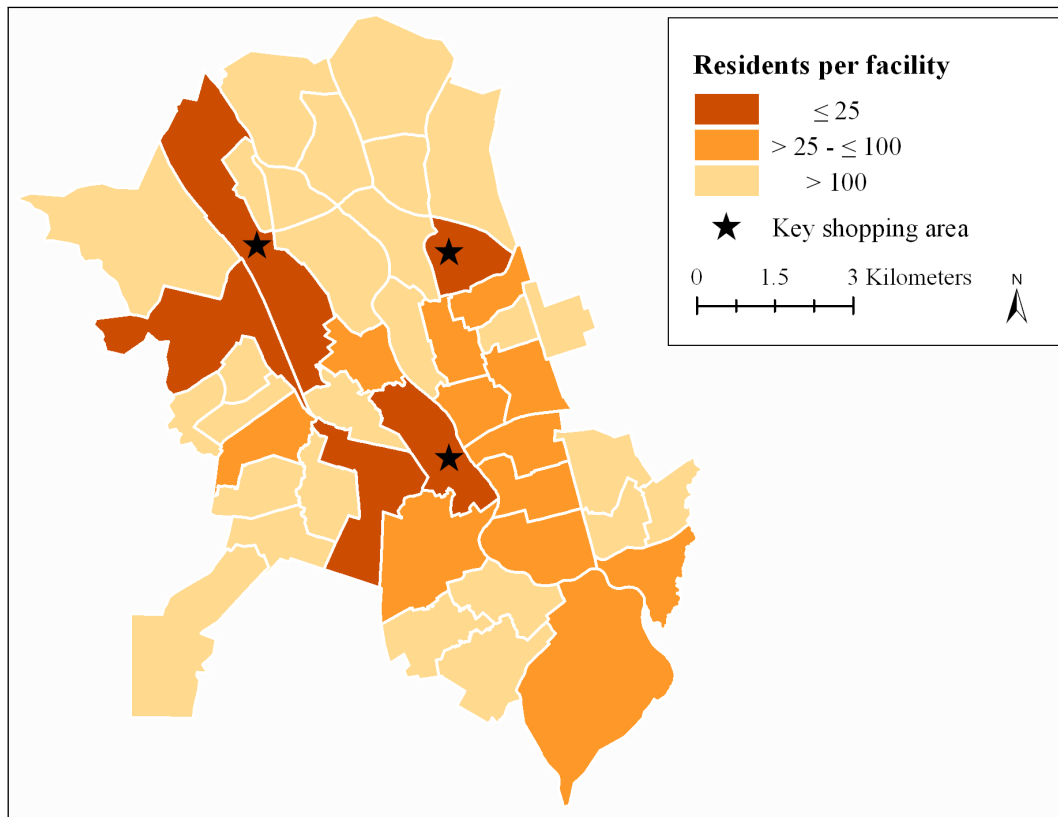


**Figure 6.39:** Origin points used within the Hamilton analysis, major roads shown

### **6.3.1.3 Activity facilities**

Hamilton possesses three key shopping areas, with Chartwell and Te Awa areas located closer to the urban fringe than the central city, as shown in figure 6.36. Key shopping areas are not a direct input to the model, but do provide an indication of where activity facilities are clustered. The data used within the model is in the form of classified points, but for display the facilities have been aggregated to the census Area Unit level, with education facilities excluded, and are shown as the number of residents per facility. Higher concentrations of facilities are observed within the central city and near key shopping areas, as shown in figure 6.40.

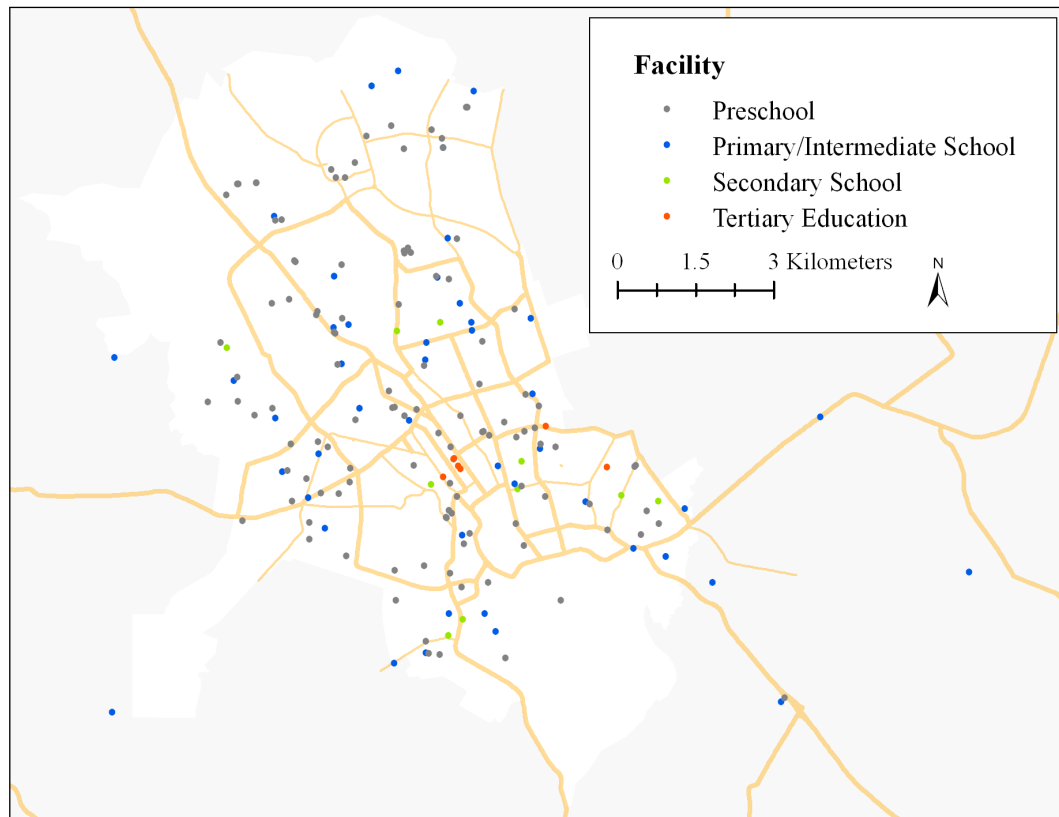




**Figure 6.40:** Density of non-education activity facilities in Hamilton at census Area Unit level

Education facilities, classified into the four types used within the model, indicate a relatively even geographic spread, with decreasing density for higher levels of education, shown in figure 6.41. The Preschool activity includes Playgroups, Play-centres, Learning Centres, Crèches, Kindergartens, Childcare Centres, Te Kohanga Reo and Preschools, which results in a high density of facilities. As with other facilities, if an education facility falls into multiple categories it will be represented once in each category, for example, a school that teaches primary thorough to high school aged children at the same location.

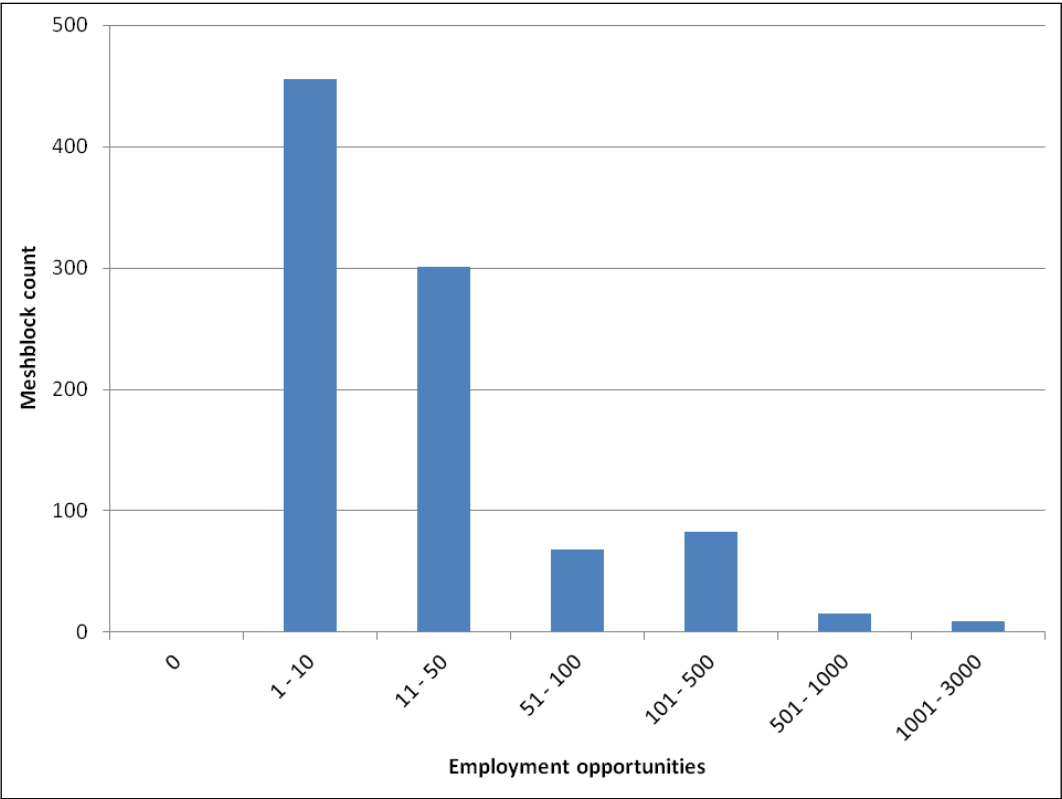
Activity facility data was derived from the *Everything from Zenbu.co.nz August 2011* community-contributed points of interest dataset, downloaded from <http://www.koordinates.com> and manually categorised into the appropriate classifications. Activity facilities from the wider Waikato region, including those lying outside the Hamilton City Council boundary, were incorporated into the analysis to avoid edge effects.



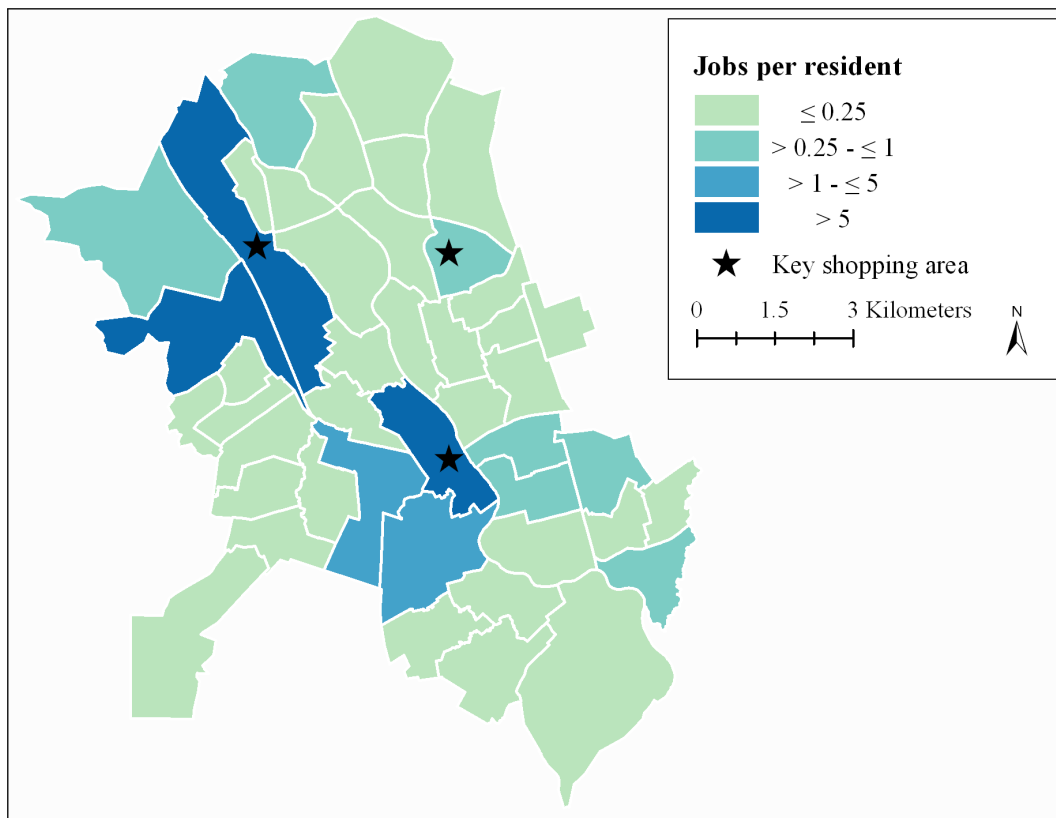
**Figure 6.41:** Spatial distribution of Hamilton education facilities

#### **6.3.1.4** *Employment facilities*

The model represents employment opportunities by proxy, through the number of potential employment opportunities per census Meshblock. This data was acquired from Statistics New Zealand as a Microsoft Excel spreadsheet and joined to the Meshblock boundary polygons file. Centroids were extracted to act as proxies for actual employment facilities. The dataset was acquired from Abley Transportation Consultants Limited. The number of employment opportunities per Meshblock ranges from three to 2,238, with a mean value of 59, shown as a frequency histogram in figure 6.42. Employment opportunity density, aggregated to the level of census Area Units and shown as the number of jobs available per resident, is greatest near key shopping areas, as shown in figure 6.43.



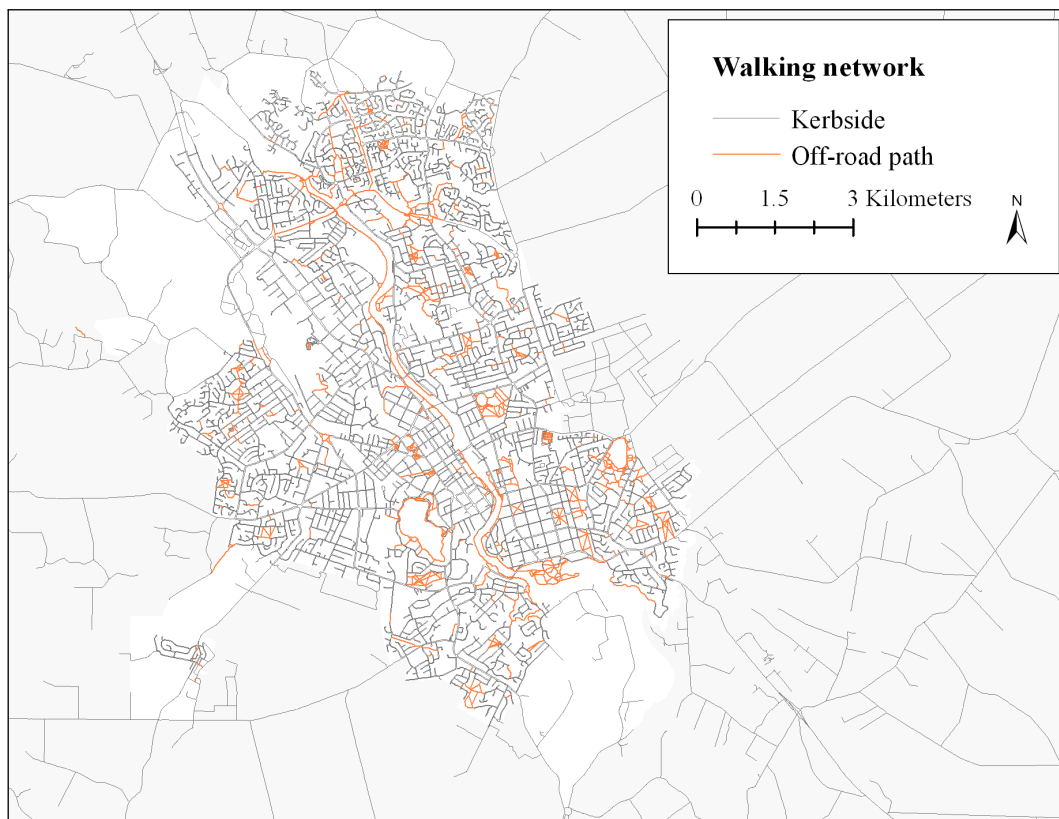
**Figure 6.42:** Frequency histogram of Hamilton employment opportunities at census Meshblock level



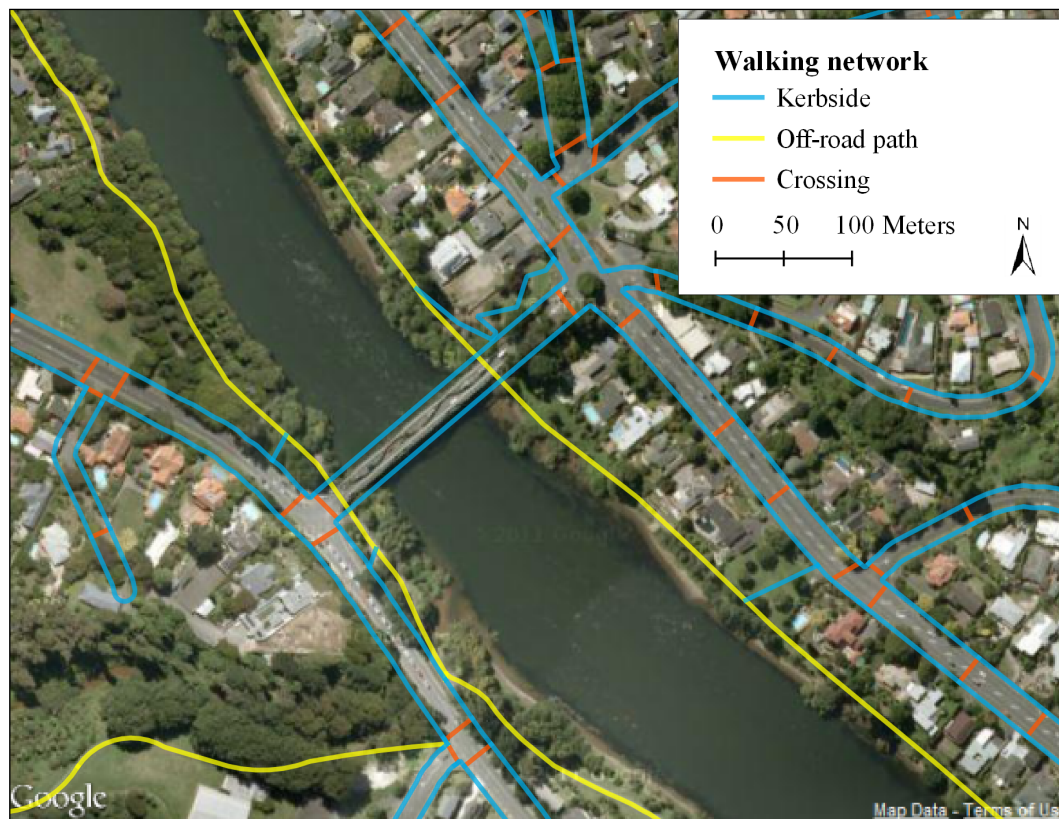
**Figure 6.43:** Density of Hamilton employment opportunities at census Area Unit level

### 6.3.1.5 Transport networks

The walking network represents roadside footpaths and off-road paths around Hamilton, as shown in figure 6.44. A detail view showing footpaths, crossings and off-road paths is presented in figure 6.45. Link traversal time is calculated based upon an assumed speed of  $4.7\text{km/h}$  (Abley & Halden, 2012). Delays for crossing streets mid-block are determined by the road vehicle volume, which is derived from regional transport models, and at signalised intersections the delays are based upon the specific signal plan at the intersection. For the Hamilton network, these delays range from 2 to 54 seconds and are fully detailed in Abley and Halden (2012). The walking network was developed by, and acquired from, Abley Transportation Consultants Limited.

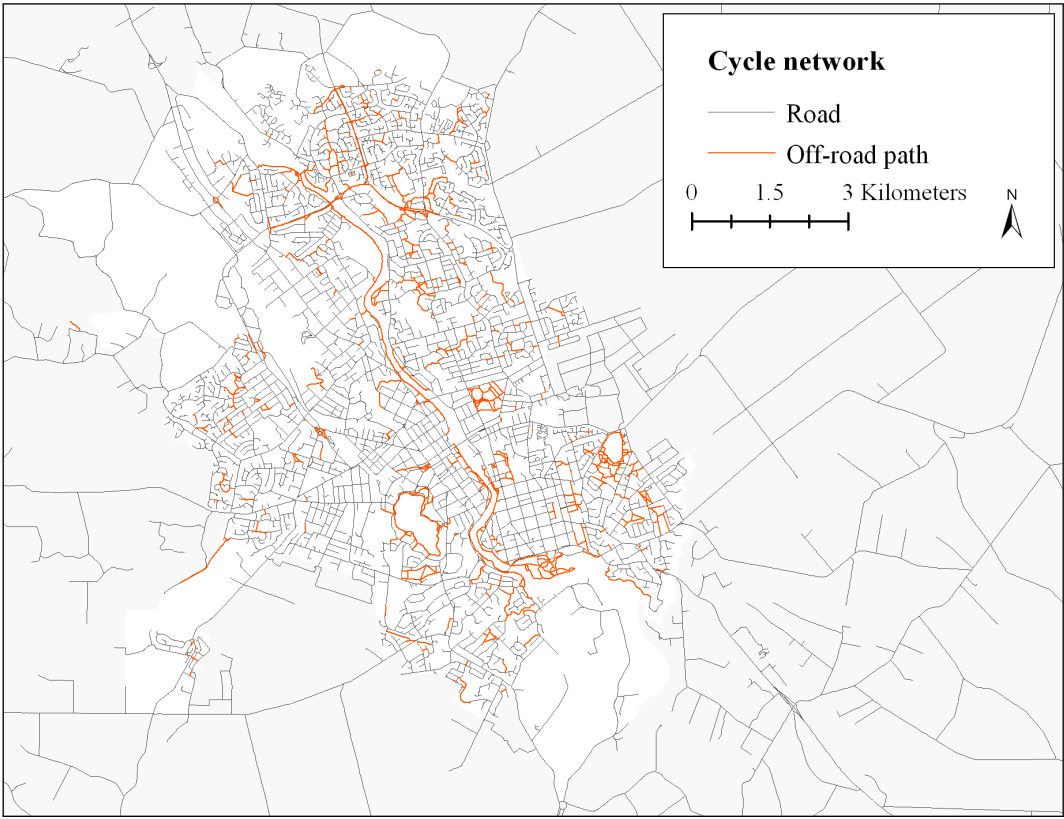


**Figure 6.44:** Hamilton walking network overview



**Figure 6.45:** Hamilton walking network detail

The cycle network is based upon the road network, although off-road paths have also been included, as shown in figure 6.46. A detailed view showing off-road paths is presented in figure 6.47. Although it is possible to include intersection delays in this type of network, they have not been included in this particular network. Link traversal times were calculated upon an assumed speed throughout the network of  $15\text{km/h}$  (Abley & Halden, 2012). The cycle network was developed by, and acquired from, Abley Transportation Consultants Limited.



**Figure 6.46:** Hamilton cycle network overview



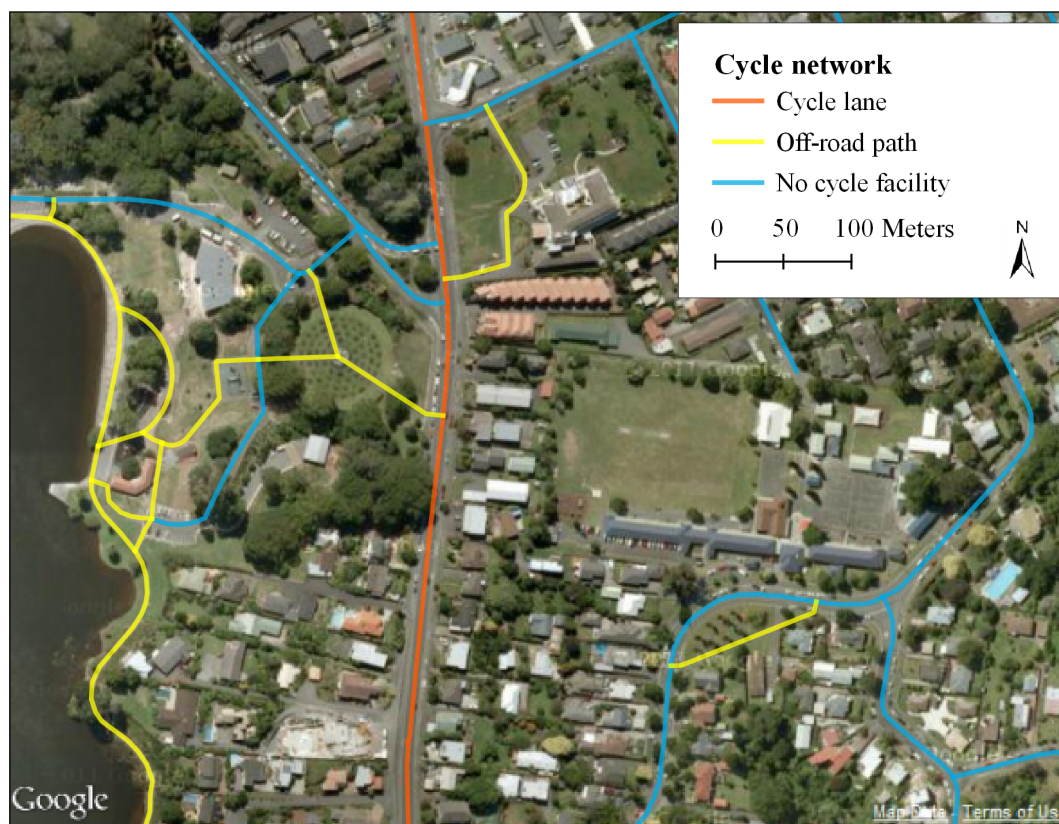
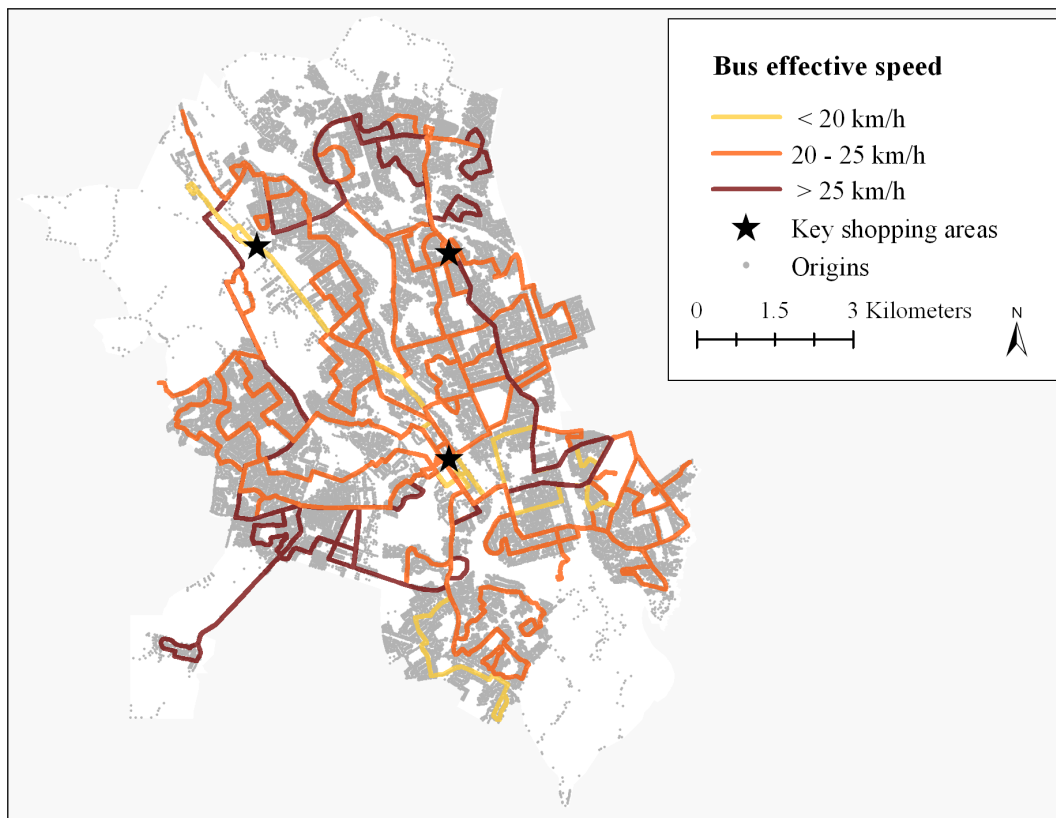


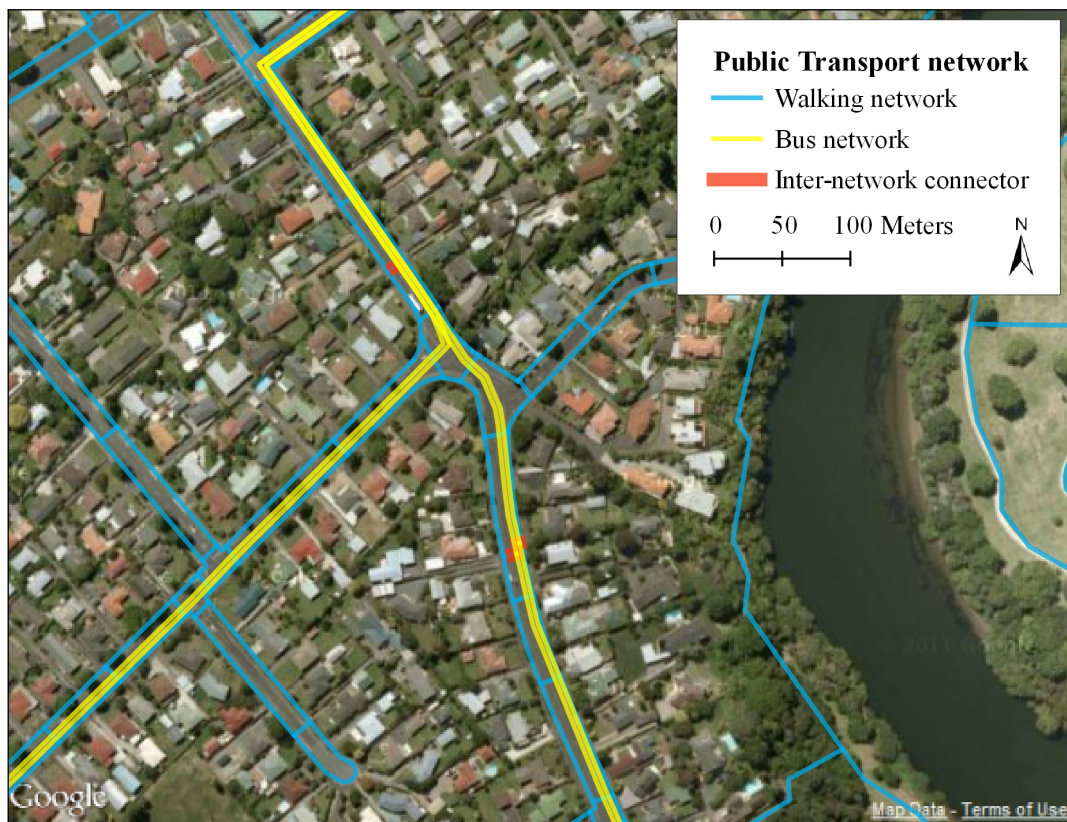
Figure 6.47: Hamilton cycle network detail



The public transport system in Hamilton consists only of buses. The network includes routes which pass through all the key shopping areas and serve the majority of residential areas, as shown in figure 6.48. The effective speed at which buses travel is lower in areas of high residential density, which typically have higher levels of congestion and a greater density of intersections. The detailed bus route maps for Hamilton city are included in appendix A.2. The public transport network includes the walking network, to capture the walking legs that are usually required at either side of the public transport journey, as shown in figure 6.49 (Abley & Halden, 2012). Stops are represented as delays, which are equivalent to half the service frequency or 7.5 minutes, whichever is the lesser (Abley & Halden, 2012). This captures the effect that passengers will tend to use schedules for low frequency services while simply walking to the bus stop and waiting for high frequency services. The data shows that most households are close to a public transport route, although this does not guarantee that the service has an appropriate frequency. The area of Rototuna contains households which may be unable to access the network as routes are too far away. Lifestyle properties to the south of the city in Peacocke, west near Temple View and Burbush, and north of Rototuna are beyond the extents of the network. The public transport network was developed by, and acquired from, Abley Transportation Consultants Limited.

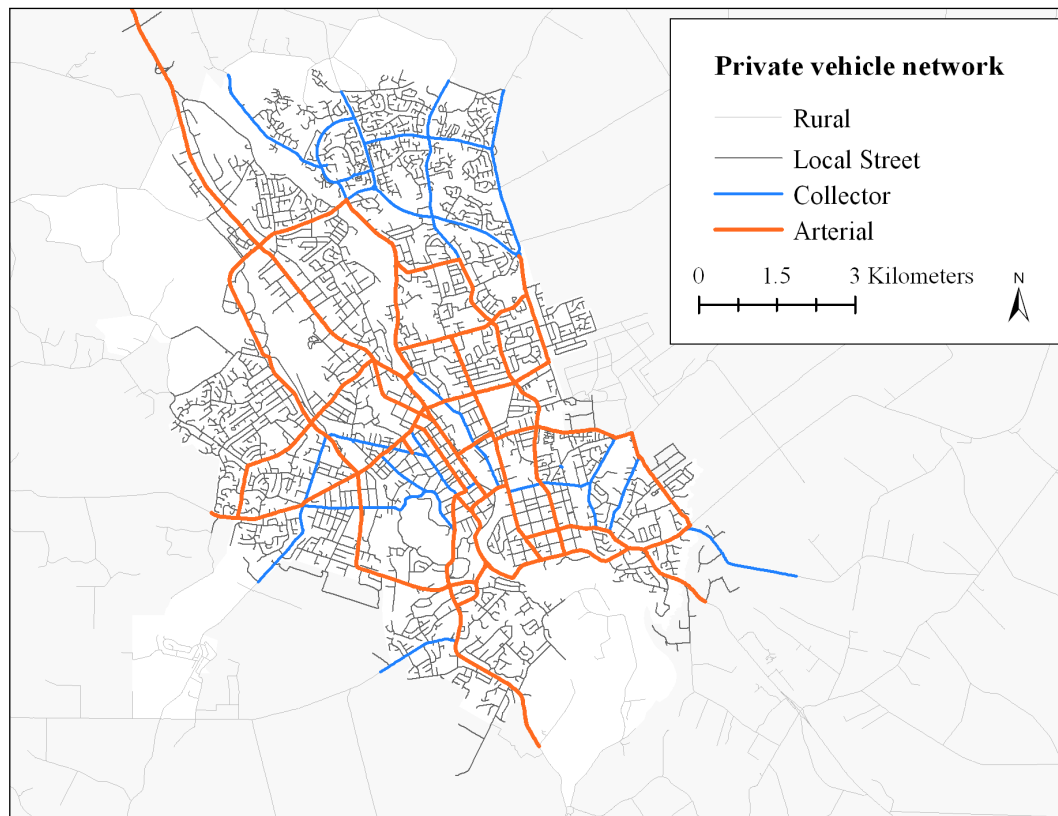


**Figure 6.48:** Hamilton public transport network overview: route outline and effective speeds



**Figure 6.49:** Hamilton public transport network detail: route specification and interface with walking network

The private vehicle network represents all roads accessible to private motor vehicles, and is shown in figure 6.50. Link traversal time is calculated based upon travel speeds derived from the Hamilton transport model. The network includes one way attributes and intersection delays. The public transport network was developed by, and acquired from, Abley Transportation Consultants Limited.



**Figure 6.50:** Hamilton private vehicle network overview

### 6.3.2 Hamilton META analysis results

Results for the Hamilton case study are presented in this section. Specific areas of the city are identified, as necessary, by name as defined in figure 6.35. The results are divided into three main parts:

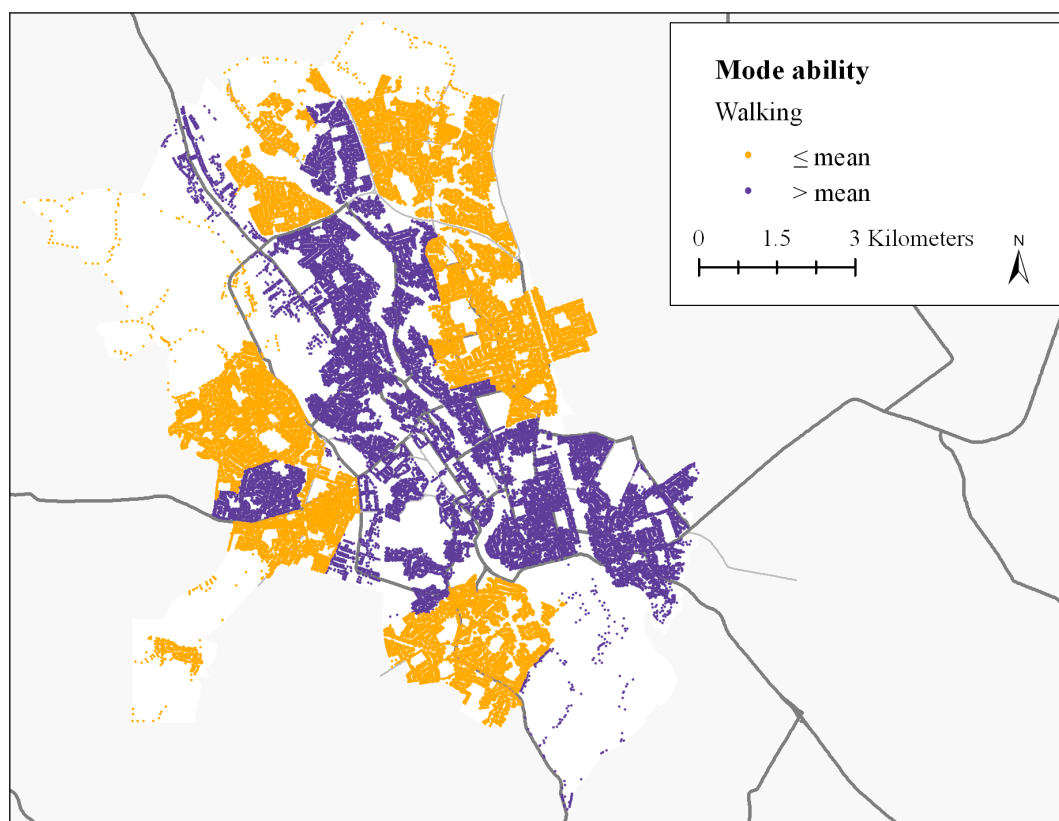
1. intermediate results, showing weighted mode abilities and total annual trips,
2. overall results, presenting the META household minimum transport energy consumption over the entire city, and
3. META mode and activity contributions, which detail the total energy consumption for travel by each mode and for travel to each activity.

**6.3.2.1 Mode ability results**

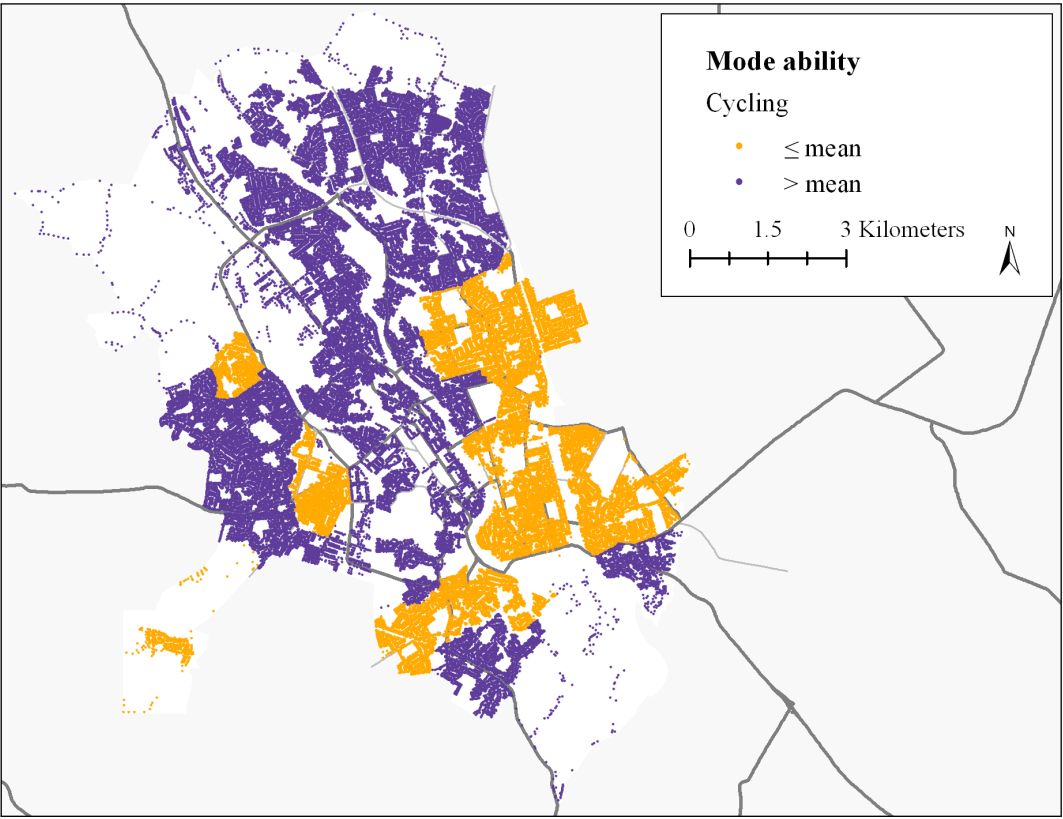
Mode abilities were weighted by census Area Unit demography, producing a spread of values which are outlined in table 6.12. The spatial distribution of weighted mode ability, displayed relative to the mean due to the low amount of variability, are shown for walking, cycling and public transport in figures 6.51, 6.52 and 6.53 respectively. The areas which are above and below the mean vary by each mode, but the variations are relatively small.

**Table 6.12:** Weighted mode abilities in Hamilton Area Units

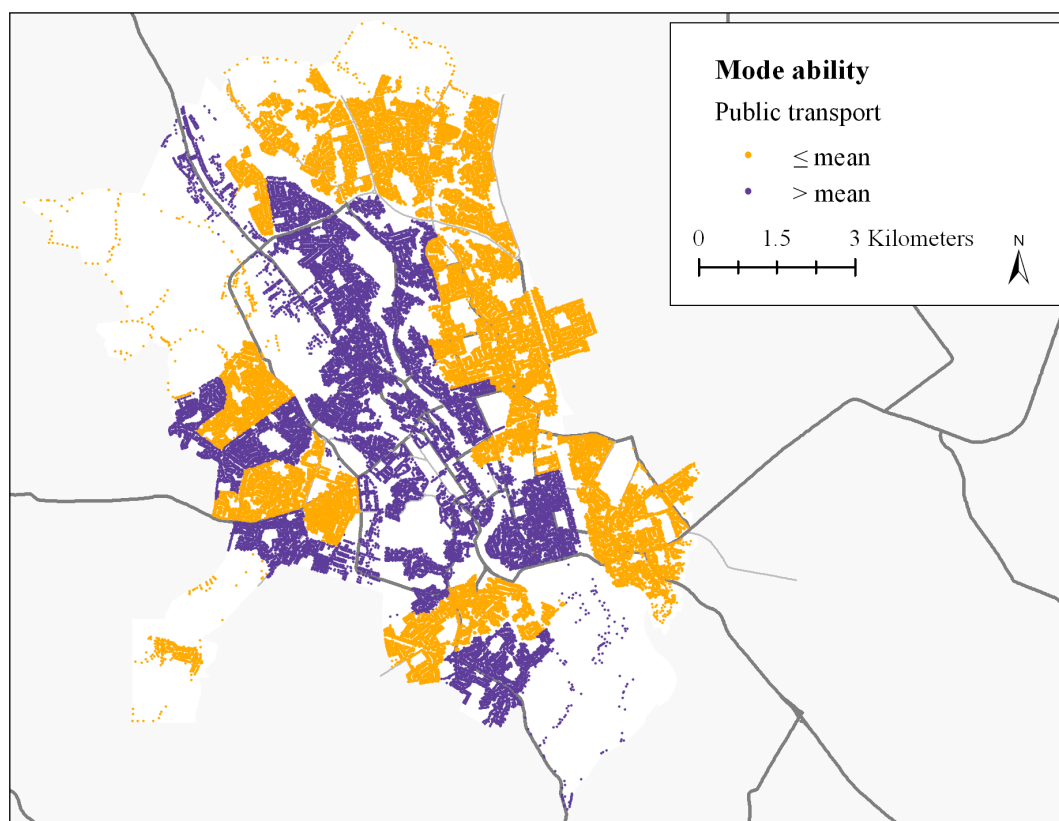
Age group	Mode ability (min)		
	Walk	Cycle	Public transport
Minimum	18.6	19.2	38.8
Mean	19.2	21.8	39.5
Maximum	19.9	22.7	40.1



**Figure 6.51:** Distribution of Hamilton walking mode ability



**Figure 6.52:** Distribution of Hamilton cycle mode ability

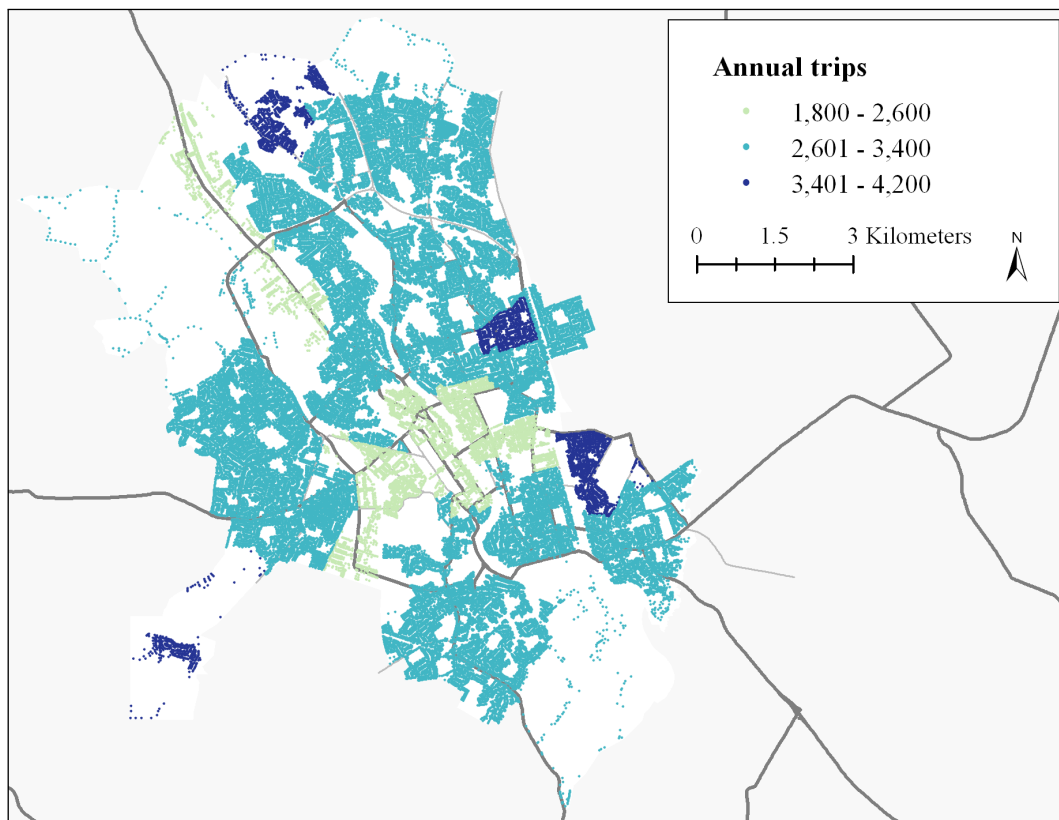


**Figure 6.53:** Distribution of Hamilton public transport mode ability



### 6.3.2.2 *Trip rate results*

The total annual number of trips for a household, which is dependent upon the resident population demography and household size, is shown in figure 6.54. It is the sum for all activities of the product of weighted frequency and trip chaining variables. There is significant variation in the annual number of trips per household, with some households making as few as 1,800 trips per year, while others making over twice that, at 4,200 annual trips. There is no obvious spatial pattern to the distribution of trip rates.

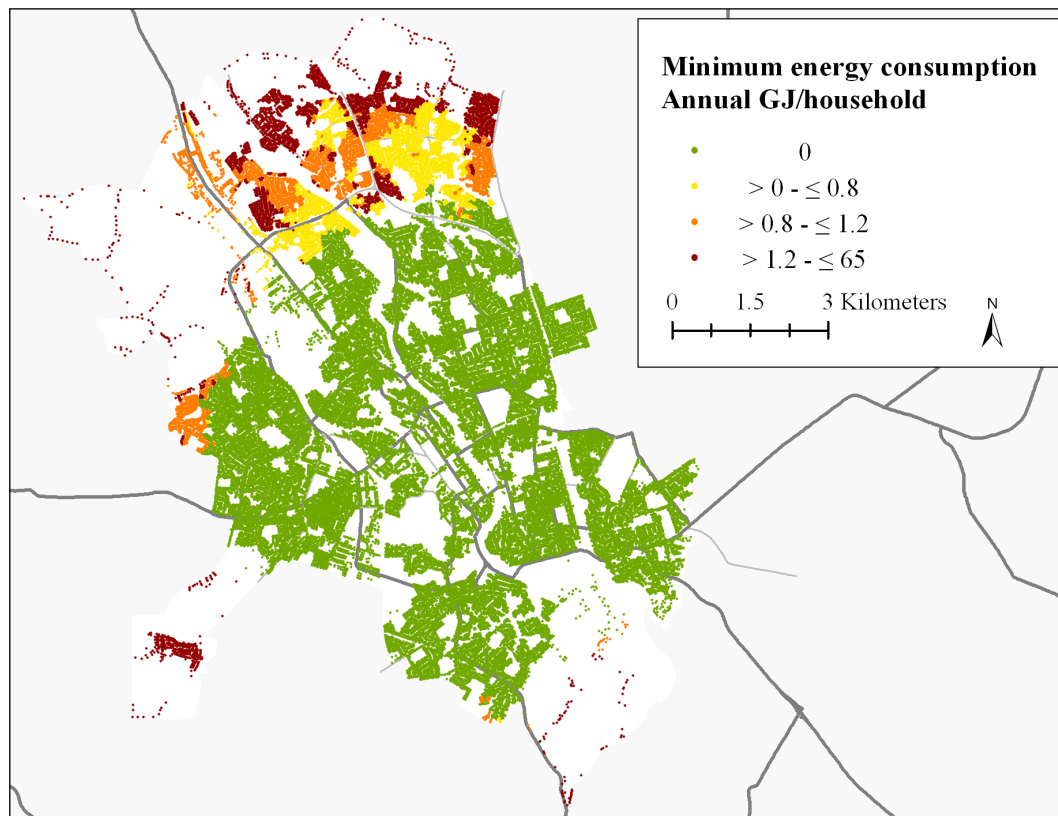


**Figure 6.54:** Distribution of Hamilton annual trip frequency

### 6.3.2.3 *META minimum energy results*

The calculated META minimum energy consumption within Hamilton is shown in figure 6.55 and summarised in table 6.13. The households shown in green lie in areas in which all META travel can be made by active modes, and thus have a minimum transport energy consumption of zero. Nearly 80% of households lie in areas that allow a zero minimum energy consumption. Yellow, orange and red households require greater amounts of energy to satisfy their transport requirements. For households with

a non-zero energy consumption the classification scheme is defined by equal percentiles, such that each group contains approximately the same number of households. Further away from the central city, particularly towards the north and west, areas require greater amounts of transport energy for residents to meet their activity needs. The key outlying areas of Peacocke, Temple View, Burbush and Rototuna all contain a high proportion of households in the highest consumption category.



**Figure 6.55:** Distribution of Hamilton annual household META minimum transport energy consumption

**Table 6.13:** Annual Hamilton household META minimum transport energy consumption

Classification ( <i>Annual <math>\frac{GJ}{household}</math></i> )	Number of households	Percent of households
0	40,960	77.9
$> 0 - \leq 0.8$	3,996	7.6
$> 0.8 - \leq 1.2$	3,633	6.9
$> 1.2 - \leq 65$	3,969	7.6
<b>Total</b>	52,558	100.0

#### 6.3.2.4 META modal contributions

The META minimum energy value is the sum of travel by private vehicle and public transport, the following figures show the specific contribution of each of these modes to the total minimum energy value. Both are displayed with a classification scheme applying the same break values as defined for the overall minimum energy consumption shown in figure 6.55, but cut off at the highest value calculated for travel by the mode. Results are summarised in table 6.14. Households shown in grey lie in areas that do not require energy consumption by the specified mode. Travel modes for a trip are assigned by the minimum energy mode hierarchy, such that any trip for which public transport is viable is made by public transport, trips for which private vehicle is the only option are made by private vehicle.

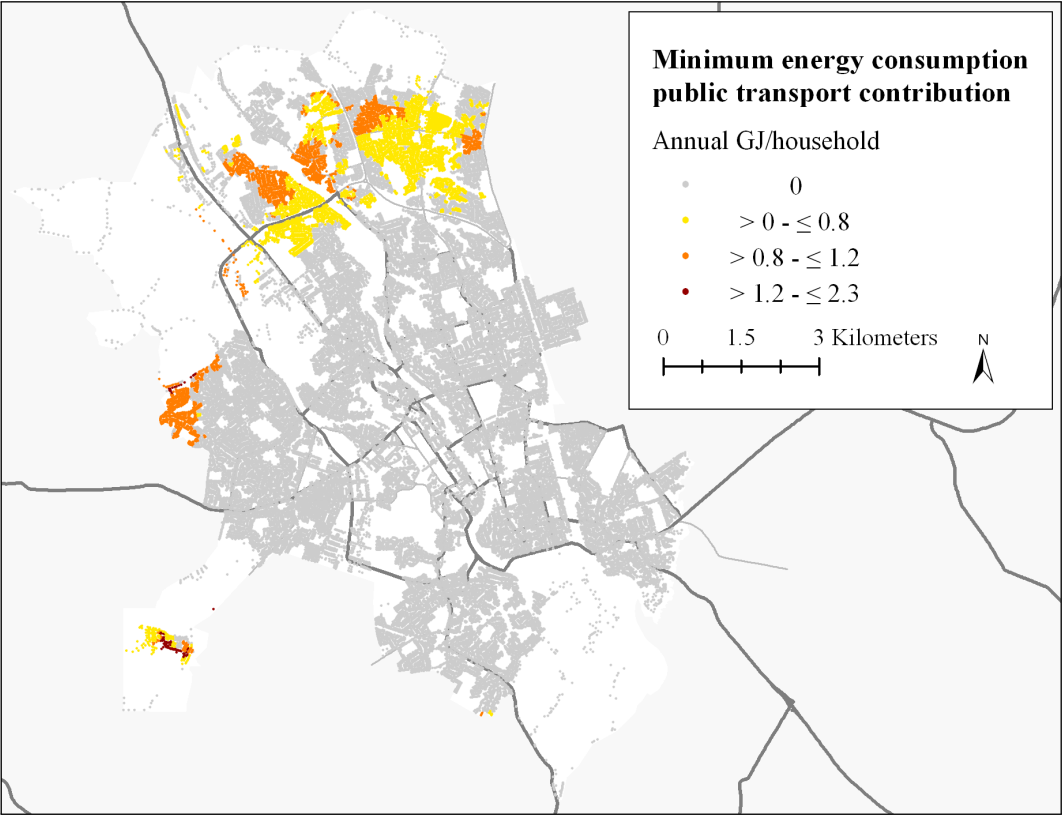
The contribution of public transport travel to META minimum energy consumption is shown in figure 6.56. As also shown in the overall META energy consumption figure, households near the centre of the city can travel without consuming any energy, including by public transport. The META results indicate nearly 13% of households lie in areas that require some travel by public transport. In general, households in areas further from the central city require greater amounts of energy. However, households in areas without access to the public transport network can be observed in Peacocke, Temple View, Burbush and Rototuna as areas of zero public transport energy consumption lying beyond energy consuming areas. Areas with lower energy consumption that are located beyond those of medium or high consumption indicate where public transport may not be viable for all household activities, and can be

**Table 6.14:** Modal contributions to Hamilton annual household META minimum transport energy consumption

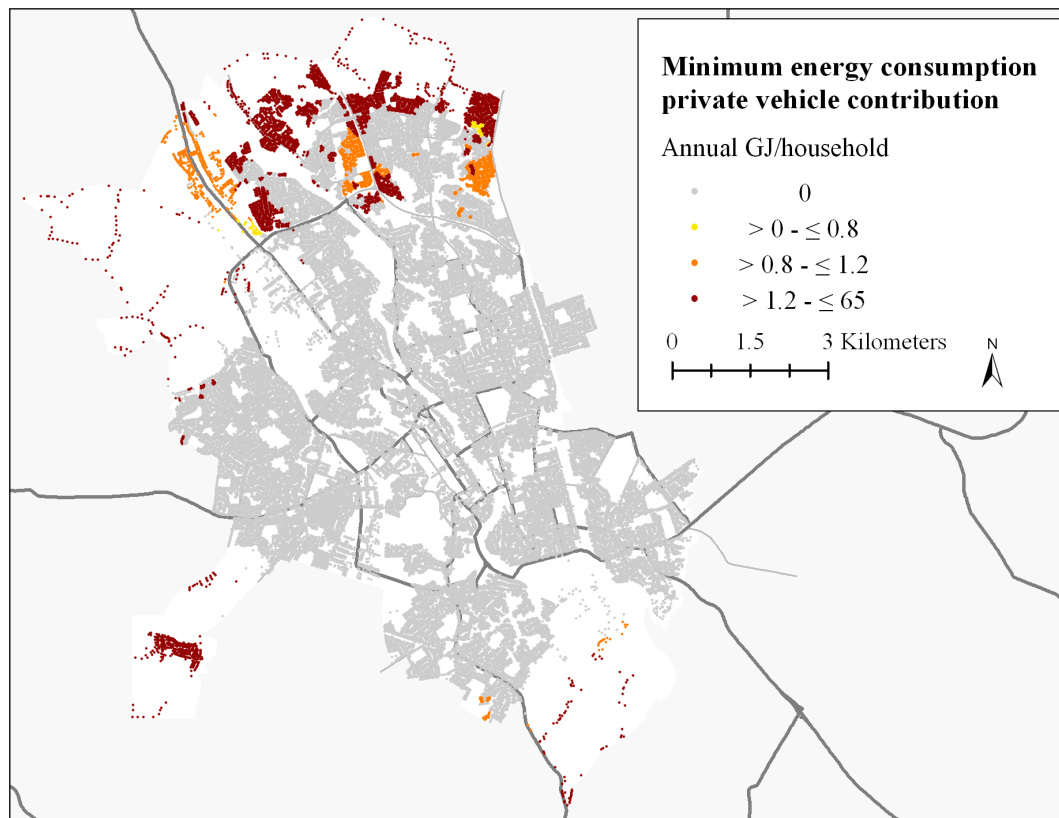
Mode	Classification ( <i>Annual <math>\frac{GJ}{household}</math></i> )	Number of households	Percent of households
Public transport	0	45,777	87.1
	$> 0 - \leq 0.8$	4,273	8.1
	$> 0.8 - \leq 1.2$	2,428	4.6
	$> 1.2 - \leq 2.3$	80	0.2
Private vehicle	0	47,316	90.0
	$> 0 - \leq 0.8$	81	0.2
	$> 0.8 - \leq 1.2$	1,256	2.4
	$> 1.2 - \leq 65$	3,905	7.4
<b>Total</b>		52,558	100.0

observed in Rototuna. The maximum META public transport energy consumption figure is  $2.3 \text{ GJ}/\text{household}$  per year.

The contribution of private vehicle travel to minimum energy consumption is shown in figure 6.57. As a result of the mode assignment hierarchy, this figure shows which households lie in areas lacking access to the public transport network or are unable to use public transport for the all of their trips. Ten percent of Hamilton households are in areas that require some travel by private vehicle, but most of these, seven percent of all Hamilton households, fall into the highest consumption category. The areas of Peacocke, Temple View, Burbush and Rototuna predominantly feature households in the highest consumption category. The maximum META private vehicle energy consumption figure is  $65 \text{ GJ}/\text{household}$  per year.



**Figure 6.56:** Distribution of public transport contribution to Hamilton annual household META transport energy consumption

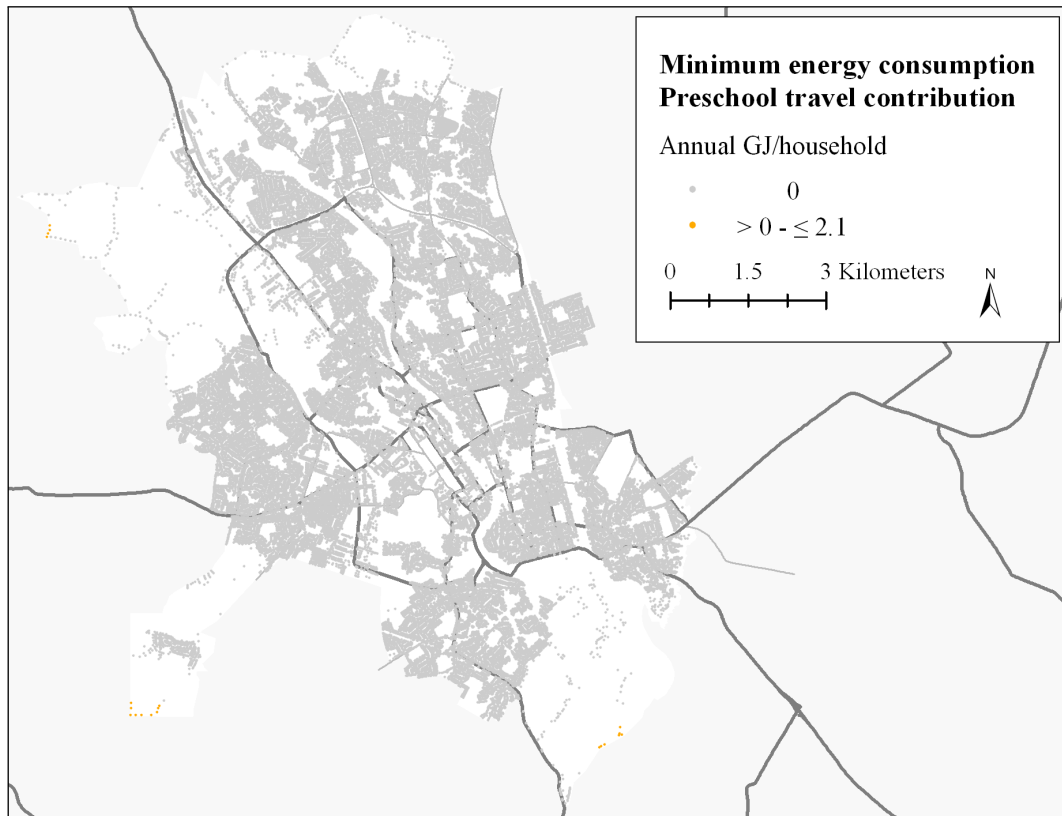


**Figure 6.57:** Distribution of private vehicle contribution to Hamilton annual household META transport energy consumption

### 6.3.2.5 META activity contributions

The META minimum energy value is the sum of annual travel to each activity, the following figures show the specific contribution of each activity to the total minimum energy value. The figures are displayed with a consistent classification scheme applying the break values from the highest META minimum energy activity, *Shopping*, as shown in figure 6.64, but cut off at the highest value calculated for travel to the activity. Results are summarised in table 6.15. Households shown in grey do not consume energy in travelling to the specified activity.

Under the META assumptions only 20 households lie in areas requiring energy consumption to reach Preschool facilities. Households that do require travel for this activity typically lie in areas on the very fringes of the city in the lifestyle areas of Peacocke and Burbush, and near Temple View, as shown in figure 6.58. The energy requirement in all areas of reaching this activity is less than half a Gigajoule per year.



**Figure 6.58:** Distribution of Preschool travel contribution to Hamilton annual household META transport energy consumption

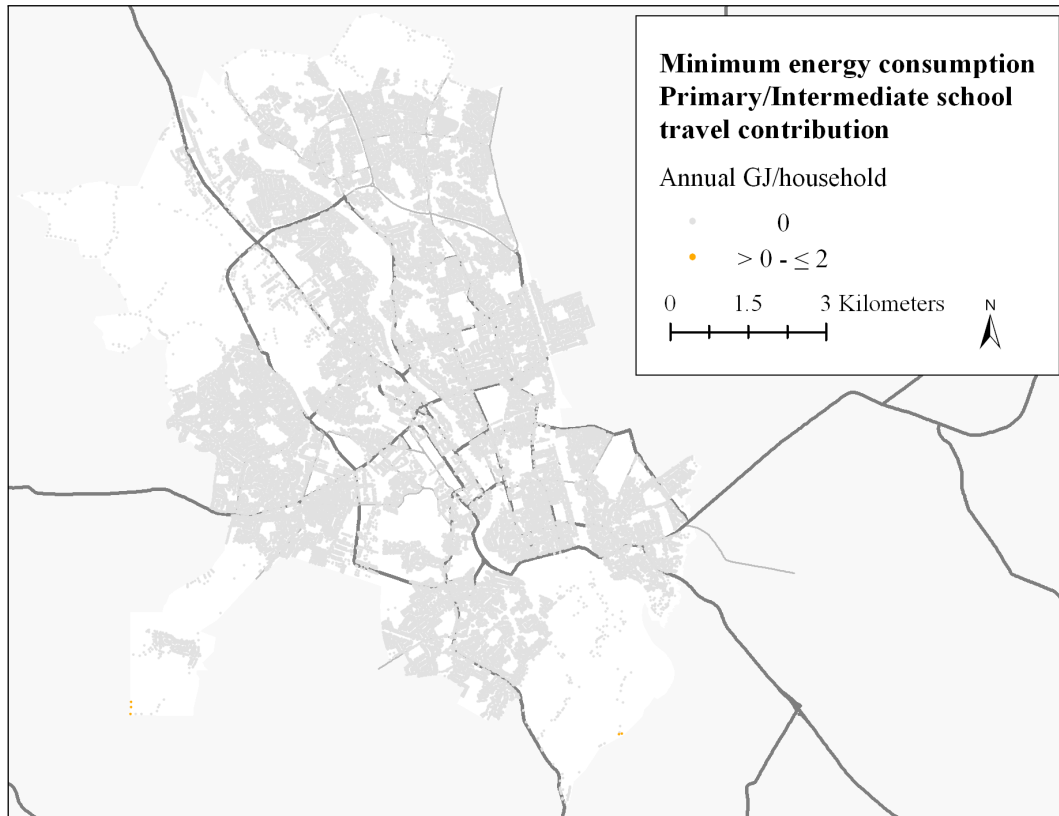
Under the META assumptions only five households lie in areas requiring energy consumption to reach Primary/Intermediate school facilities, as shown in figure 6.59. All

**Table 6.15:** Activity contributions to annual Hamilton household META minimum transport energy consumption

Activity	Classification ( <i>Annual <math>\frac{GJ}{household}</math></i> )	Number of households	Percent of households
Preschool	0	52,538	100.0
	$> 0 - \leq 2.1$	20	$\approx 0.0$
Primary/Intermediate school	0	52,553	100.0
	$> 0 - \leq 2$	5	$\approx 0.0$
Secondary school	0	50,706	96.5
	$> 0 - \leq 3$	1,852	3.5
Tertiary education	0	40,960	77.9
	$> 0 - \leq 3$	11,598	22.1
Medical/dental	0	52,468	99.8
	$> 0 - \leq 1$	90	0.2
Personal business	0	52,463	99.8
	$> 0 - \leq 4$	75	0.1
	$> 4 - \leq 8$	20	$\approx 0.0$
Recreation	0	52,558	100.0
Shopping	0	52,375	99.7
	$> 0 - \leq 4$	56	0.1
	$> 4 - \leq 8$	64	0.1
	$> 8 - \leq 20$	63	0.1
Social visits	0	52,522	99.9
	$> 0 - \leq 4$	13	$\approx 0.0$
	$> 4 - \leq 8$	6	$\approx 0.0$
	$> 8 - \leq 15$	17	$\approx 0.0$
Employment	0	51,900	98.7
	$> 0 - \leq 4$	485	0.9
	$> 4 - \leq 8$	138	0.3
	$> 8 - \leq 13$	35	0.1
<b>Total</b>		52,558	100.0



the households that do are lifestyle properties on the fringes of the council jurisdiction, in Peacocke and near Temple View. The energy requirement in all areas of reaching this activity is no more than two Gigajoules per year.

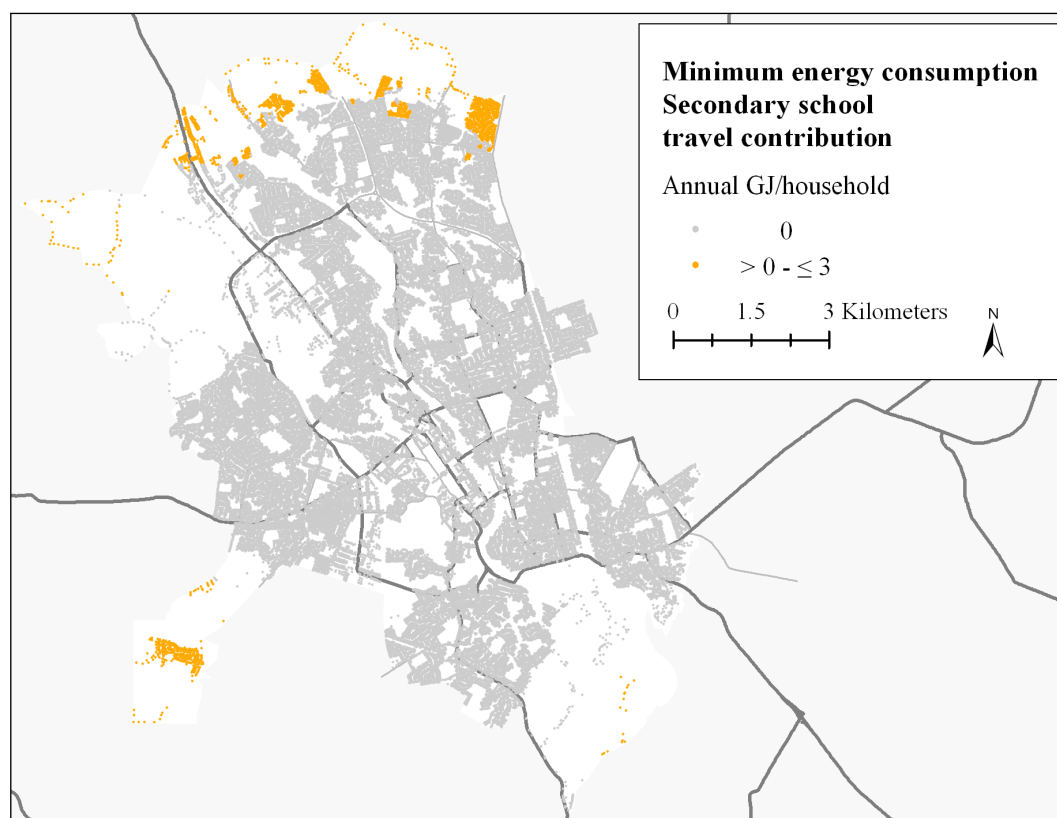


**Figure 6.59:** Distribution of Primary/Intermediate school travel contribution to Hamilton annual household META transport energy consumption

Less than four percent of households lie in areas requiring some energy consumption in reaching Secondary school facilities, as shown in figure 6.60. A large proportion of the households in Temple View require energy to travel to this activity, as do households in Peacocke, Burbush and Rototuna. The energy requirement in all areas of reaching this activity is no more than three Gigajoules per year.

Over 20% of households lie in areas requiring some energy consumption to reach Tertiary education facilities, as shown in figure 6.61. As these facilities are clustered in the centre and east of the city, energy is required for travel from areas in the north, west and south of the city. The energy requirement in all areas of reaching this activity is not more than three Gigajoules per year.

Much less than one percent of households lie in areas requiring energy consumption to reach Medical/Dental facilities, as shown in figure 6.62. All these households are in



**Figure 6.60:** Distribution of Secondary school travel contribution to Hamilton annual household META transport energy consumption

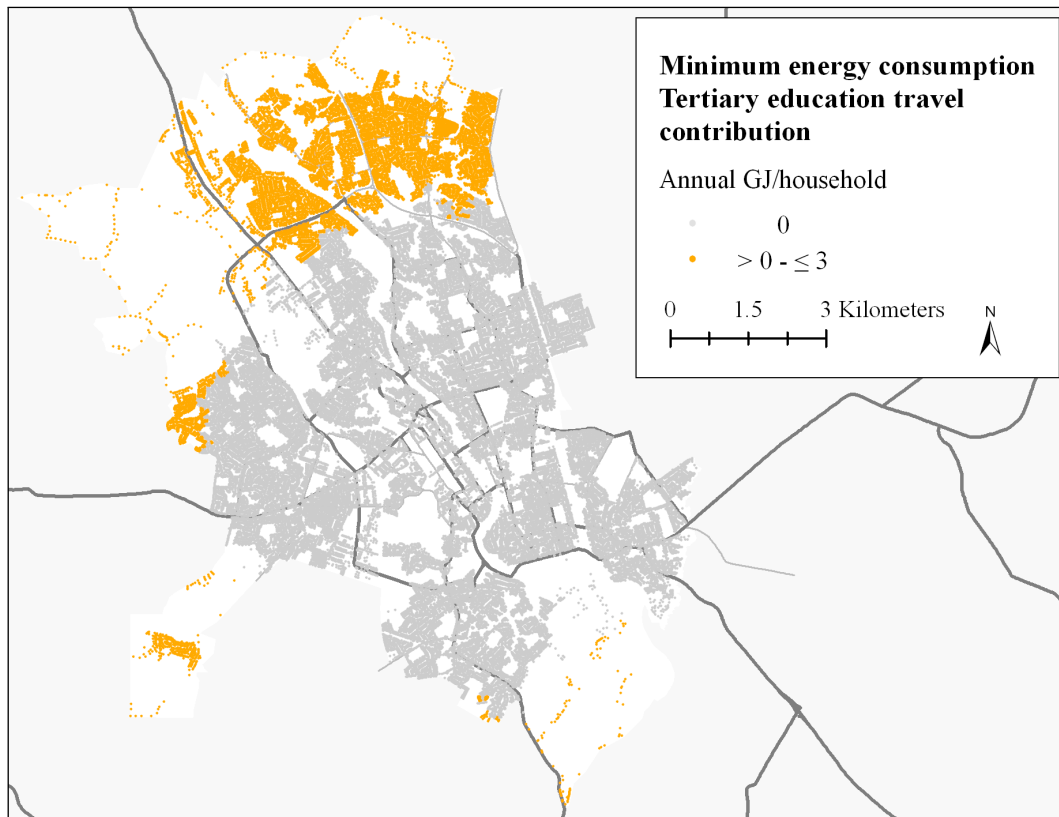
lifestyle areas Peacocke, beyond Temple View and in Burbush. The energy requirement for all households in reaching this activity is not more than one Gigajoule per year.

Much less than one percent of households lie in areas requiring energy consumption to reach Personal/Business facilities, as shown in figure 6.63. Areas requiring energy consumption to reach this activity are located on the fringes of the city in Peacocke and Burbush, and beyond Temple View and Rototuna. The energy requirement for all households in reaching this activity is not more than eight Gigajoules per year.

No areas in Hamilton require household transport energy consumption to reach Recreational facilities.

Much less than one percent of households lie in areas requiring energy consumption to reach Shopping facilities, as shown in figure 6.64. The lifestyle areas of Peacocke and Burbush, and households beyond Temple View and Rototuna all require significant amounts of energy to reach this activity. The annual requirement in reaching this activity is as high as twenty Gigajoules per year in some areas.

Much less than one percent of households lie in areas requiring energy consumption to reach Social visit facilities, as shown in figure 6.65. Few areas require energy



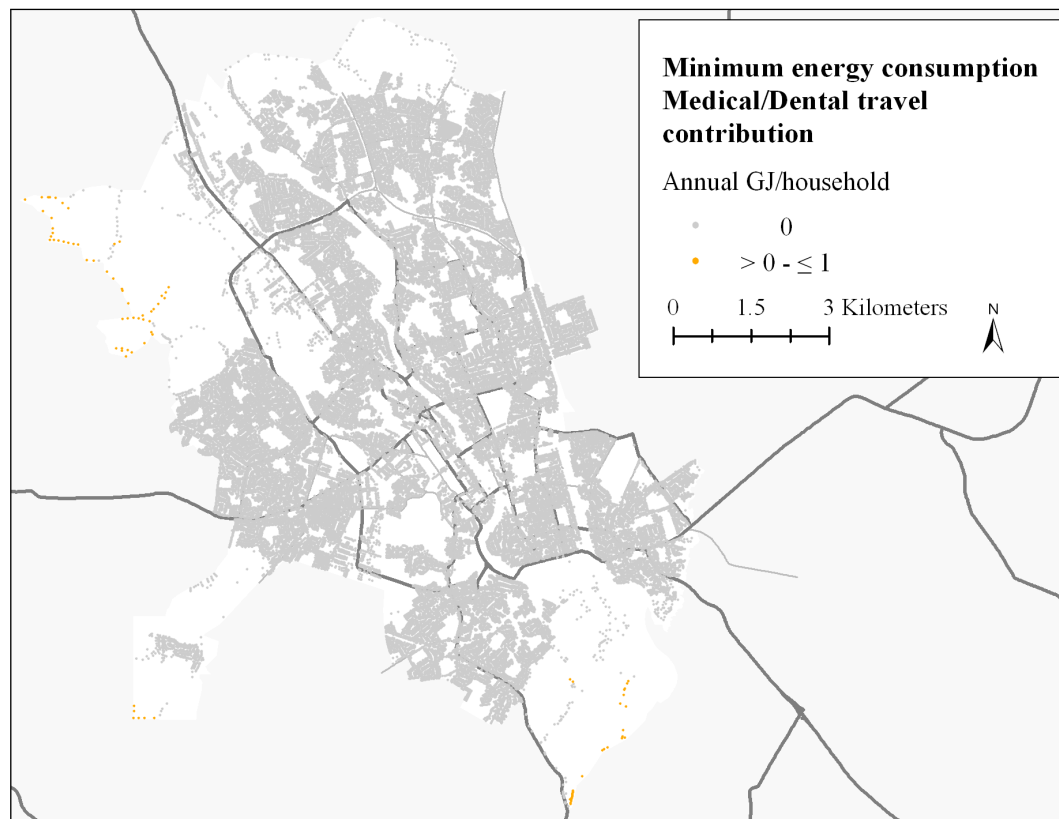
**Figure 6.61:** Distribution of Tertiary education travel contribution to Hamilton annual household META transport energy consumption

consumption to reach this activity, and are limited to lifestyle areas in Peacocke and Burbush and beyond Temple View. The annual requirement in reaching this activity is as high as fifteen Gigajoules per year.

Over one percent of households lie in areas requiring energy consumption to reach Employment facilities, as shown in figure 6.66. Households that do require travel for this activity typically lie in areas on the city fringes, including Peacocke and Burbush, as well as parts of Temple View and Rototuna. The annual requirement in reaching this activity is as high as thirteen Gigajoules per year in some areas.

### 6.3.3 Summary of Hamilton results

Nearly 80% of households in Hamilton lie in areas that do not require transport energy consumption under the assumptions of the META model. This indicates that the majority of Hamilton households will be at low exposure to future energy supply constraints. However, residential and lifestyle areas on the extreme fringes of the city, such as Rototuna, Peacocke and Burbush, and outlying the town of Temple View

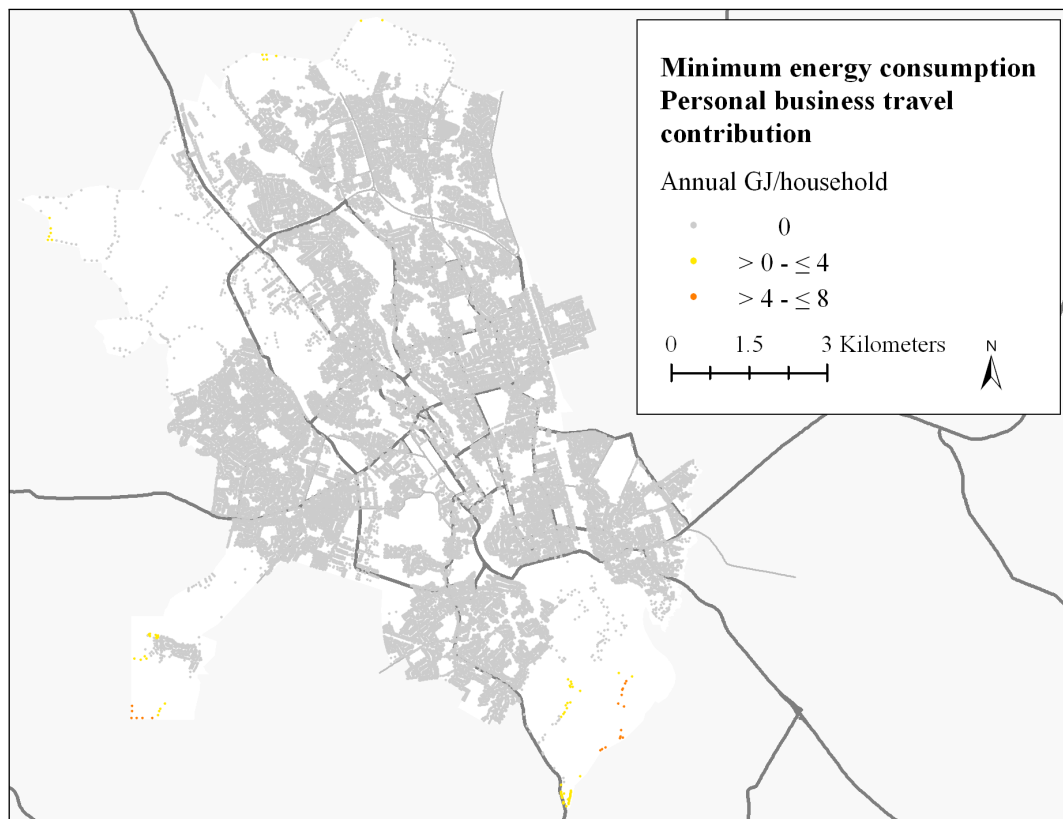


**Figure 6.62:** Distribution of Medical/Dental travel contribution to Hamilton annual household META transport energy consumption

require that residents consume significant amounts of transport energy in reaching their destinations. These areas severely limit the number and extent of adaptive responses open to residents.

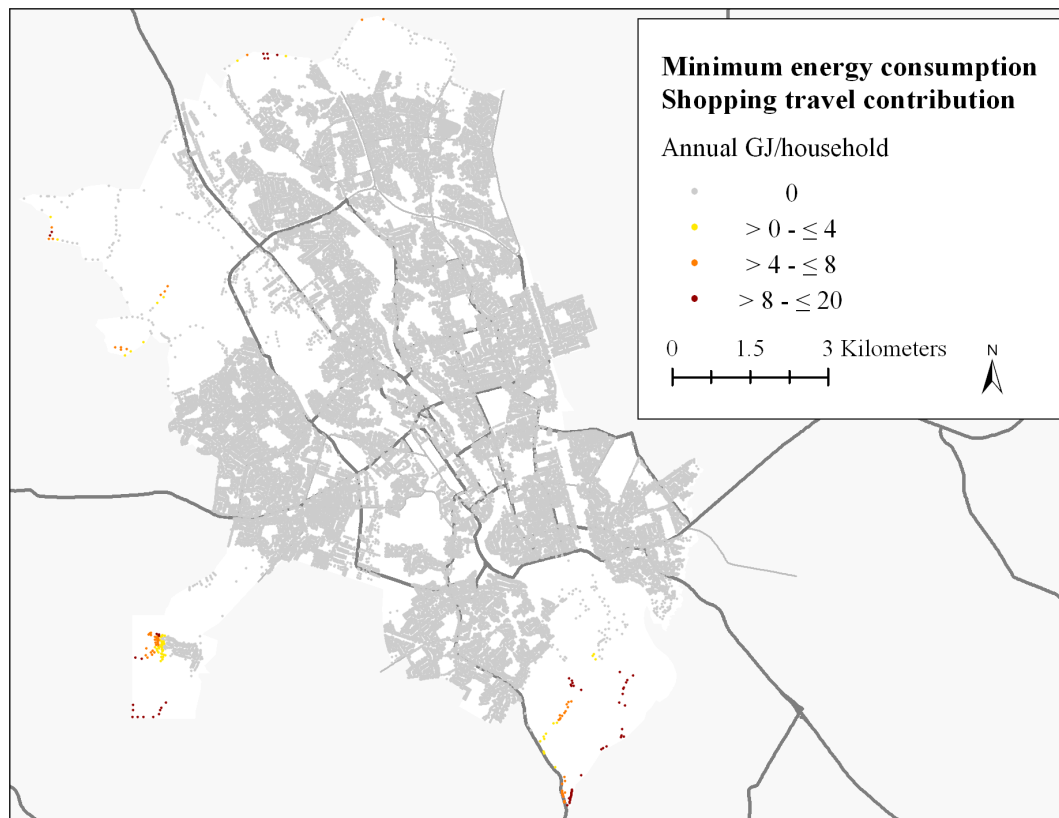
Analysing the minimum energy results by mode highlights the mode limitations imposed by the urban form, particularly those areas lacking access to public transport, and areas in which public transport is not viable for all trips. A lack of access to the network is a significant issue for households in Rototuna, to the north of the city, and the outlying town of Temple View. Lifestyle areas in Peacocke, near Temple view and in Burbush also lack access, but represent a small population. Southern and south-western parts of Rototuna also highlight gaps in access to or access of the public transport network. Parts of Temple View fall in the highest consumption categories for both private vehicle and public transport modes.

Viewing results by activity contribution to the META minimum energy requirement indicates the activity limitations of the urban form. Activities which are accessed less frequently contribute less to the total energy requirement, although they may still be important for certain demographic profiles. A few areas require energy consumption

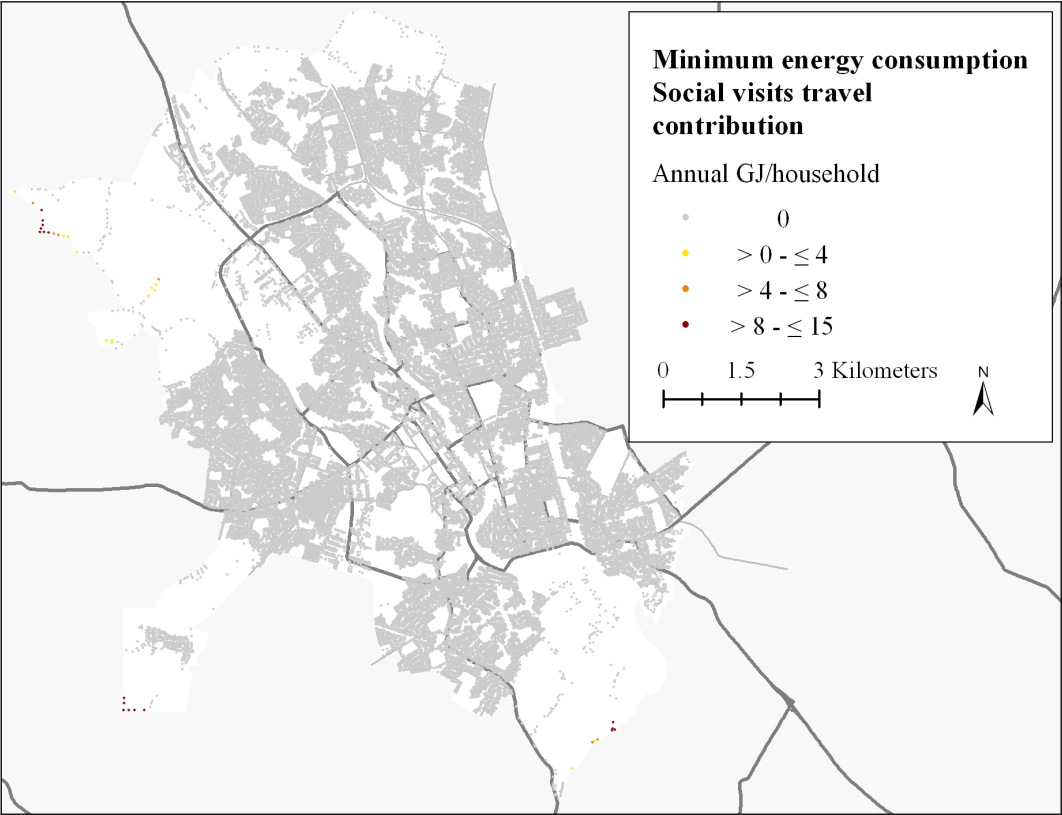


**Figure 6.63:** Distribution of Personal business travel contribution to Hamilton annual household META transport energy consumption

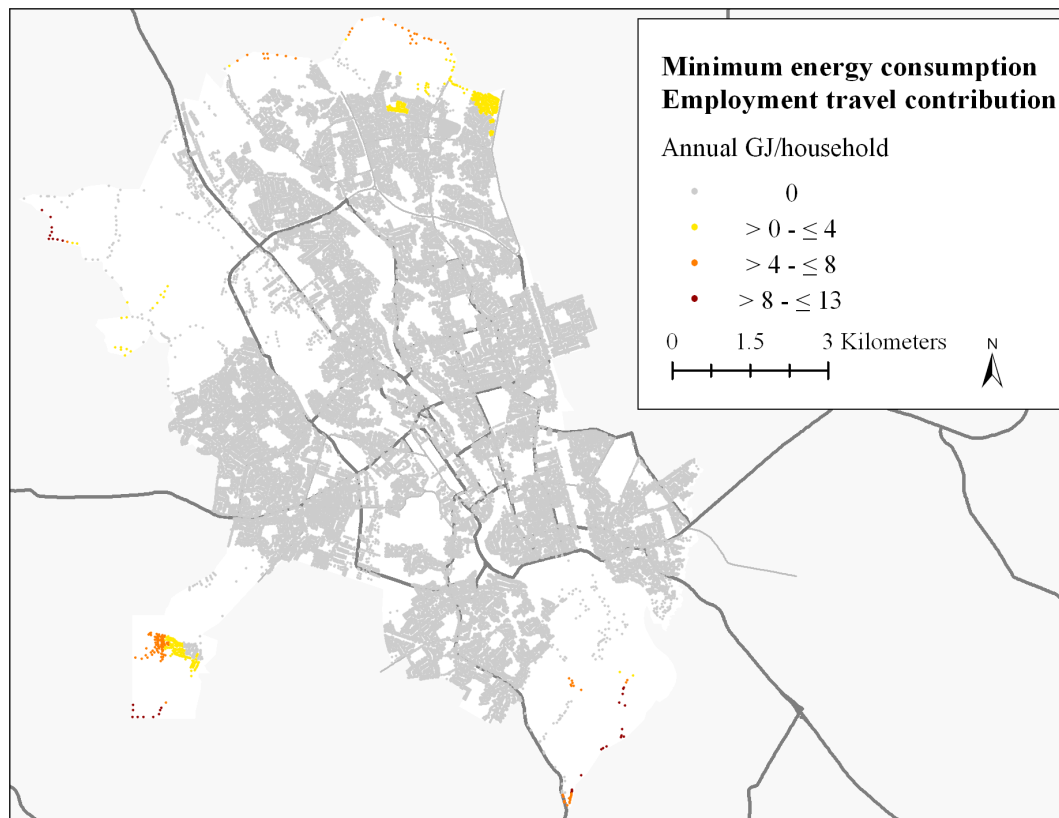
for almost all activities notably the lifestyle areas of Peacocke, Burbush, near Temple View and north of Rototuna, the northern parts of the suburb of Rototuna and the outlying town of Temple View.



**Figure 6.64:** Distribution of Shopping travel contribution to Hamilton annual household META transport energy consumption



**Figure 6.65:** Distribution of Social visits travel contribution to Hamilton annual household META transport energy consumption



**Figure 6.66:** Distribution of Employment travel contribution to Hamilton annual household META transport energy consumption



## 6.4 Discussion of case study results

The case studies of Christchurch and Hamilton have shown that the majority of areas in both these cities have a META minimum energy requirement of zero, and thus allow residents to significantly adapt their transport energy consumption in the face of future energy supply constraints. However, outlying towns, fringe suburbs and lifestyle properties consistently require significant amounts of META minimum transport energy, and thus severely limit the number and extent of adaptive responses available to residents. These results are analysed at the city level, although analysis at levels of detail as fine as the household is possible.

Compared to Christchurch a greater proportion of the areas in Hamilton have a META energy requirement of zero. The distance that can be covered by cycling, which is the product of network speed and cycling ability, ranges from 4.8 to 5.7 km in Hamilton. With the exception of households in outlying towns, lifestyle properties and fringe suburbs to the north, most areas in Hamilton are within this distance of the central city, and hence of a large number of activity facilities. Christchurch is larger than Hamilton, spreading out particularly to the north, east and west, with a number of areas further from the central city than the Christchurch cycle-able distance of 4.9 to 5.8 km. Consequently, a greater proportion of households require transport energy. The topography of Christchurch also limits adaptability in certain areas, such as Southshore, which is located on a peninsula with only one connection to the city, and Lyttelton, which effectively possesses no active mode links to the city.

In both cities the outlying towns that contain only a limited number of activity facilities have low adaptability. These include Lyttelton and Templeton near Christchurch and Temple View near Hamilton. Residents of these areas must use infrequent and slow public transport or drive into the city to meet most of their activity needs. Although the “lifestyle” aspects of these areas may have attracted residents in the past, the transport costs of living there in the face of future energy supply constraints may prove insurmountable. A greater number of lifestyle properties that have few, if any, alternatives for most of their trips are included within the Hamilton city boundary than within the Christchurch city boundary. Hence, the highest annual META energy consumption value was 65 *GJ/household* in Hamilton, compared to 36 *GJ/household* in Christchurch. Although not included in these case studies, the satellite towns that rely on nearby cities for employment and other activities, such as Rolleston near Christchurch, are likely to have even greater energy requirements.

Two limitations of the model are highlighted in the results:

1. The minimum energy travel for Tertiary education shows residents in all areas consuming energy to access this activity. In reality the most Tertiary students have selected their residential location to be near their education provider and thus to minimise their travel requirement. Consequently, the implication that many areas require travel to Tertiary education in the same way they would, for example, to Employment is incorrect. The model correctly shows that Tertiary students who do live in distant areas will have greater travel requirements, but this would comprise only a small number of households. This limitation is not easily overcome, but does indicate that all results should be viewed in context.
2. Children accessing Preschool, and some children accessing Primary school, are typically accompanied by caregivers. The model does not account for the fact that caregivers may engage in trip chaining when delivering the children, for example, dropping the child off while travelling to work. The results do still show that the activity may be difficult to access for some households.

An approach for mitigating both these limitations is discussed in chapter 7.

The results suggest a range of ways in which META minimum energy consumption may be decreased while maintaining activity participation. These fall into two broad categories.

- **Personal level** adaptive responses, which are limited to:
  - exceeding the principles or assumptions of the model by increasing trip chaining, travelling further by active and public transport modes than specified by the mode ability or increasing the number of people per vehicle for vehicle trips.
  - relocating to an area in which less energy is required to meet transport needs.
- **City level** interventions, including:
  - improving the effective speed, and thus reach, of active modes; for example, increasing pedestrian amenity through shorter crossing wait times or increasing the number and accessibility of cycle facilities.
  - increasing the accessibility to and of public transport services through careful network design, or decreasing the energy intensity of public transport through increasing patronage and efficiency.

- reducing the energy intensity of private vehicle travel by reducing congestion. However, the overall effect of this is likely to be less than that available from other measures and much less than the scale of reduction required.
- relocating activity facilities to reduce travel, although there is limited scope for this measure as destinations require nearby populations, and areas with high META energy consumption are typically lower density areas located on urban fringes.

In the absence of any city level interventions households are likely to relocate over the medium to long term to reduce their exposure to energy constraints. This will result in property price decline in areas with high energy requirements and price increases within more adaptable central areas.

In both cities improvements to active mode networks will increase the number of households with zero META energy requirements and reduce the total energy requirement of all energy consuming households. Increasing the effective speed of walking, through greater ease of crossing and prioritised signals, will make destinations more accessible by walking. Increasing the effective speed of cycling, through high quality on-road facilities and separated paths or prioritised signals, will make destinations more accessible by cycling. The results do not highlight particular active mode interventions, but these measures would improve accessibility in all areas.

The results do, however, indicate specific public transport interventions that might reduce energy requirements. The results highlight two important aspects of public transport accessibility; access *to* the public transport network and access *by* the public transport network. In both cities there are populated areas that lack access to the public transport network. These areas are seen in the results as areas of zero public transport META energy consumption located beyond areas of higher consumption. Under the assumptions of the model, households in these areas would have utilised public transport if they had access to it. In Christchurch, areas near Sumner, Hornby, Belfast and Parklands exhibit lack of access to the public transport network. In Hamilton, large areas within and north of Rototuna, and the outlying town of Temple View, exhibit lack of access to the public transport network. Public transport route changes in these areas would reduce the amount of private vehicle travel required, and thus META energy consumption. The development of “park and ride” facilities within walking or cycling distance of these areas would also reduce minimum energy consumption, but the model does not currently assess this. Examining the results in finer detail would enable identification of potential routes, and the model could be

run on hypothetical data to test the impact of these changes. Both cities also exhibit areas where public transport is viable for some trips, but not all, indicating limited access by public transport. In Christchurch the areas of Southshore, Sumner, Lyttelton, Halswell, Hornby, Templeton, Belfast and Parklands, and in Hamilton the areas of Rototuna and Temple View, all feature households with limited access by the public transport network. These results suggest that express services, which get passengers from outlying areas into key activity centres quickly, might help to decrease META energy consumption.

The scope for META energy reductions through activity facility changes alone is limited. Increasing the number of activity facilities in areas with high energy consumption, such as those on the urban fringe or outlying towns, ignores the fact that facilities require a critical number of customers within accessible distances to be viable. However, activity facility changes in conjunction with transport measures might improve adaptability. For example, redeveloping an existing urban area to increase the active mode accessibility, residential density and number of activity facilities around a public transport hub providing good links to key activity centres. This would allow a low minimum energy for new residents and improve the adaptability of nearby areas. Increasing the residential density provides customers for facilities and patrons for public transport. Active mode links enable local residents to access nearby destinations without energy consumption and to access the public transport hub, enabling quick transport to a greater number of activity facilities.

The results also indicate that areas of extremely low residential density which are far from activities, such as the lifestyle properties seen around Hamilton in the areas of Peacocke and Burbush, north of Rototuna, and near Temple View, will be highly exposed to future fuel constraints. Unless residents alter their travel patterns significantly to undertake high levels of trip chaining or engage in many of their activities without travelling, these areas are likely to become exceedingly expensive to reside in, and may face significant future decline.

## 6.5 Consequences for other cities

On an international scale both Christchurch and Hamilton are small cities, and both have an average overall study area urban residential density of approximately 14 persons per hectare. This places them within the expected range for automobile cities, of 10 to 20 persons per hectare, as described in chapter 2.

As also outlined in chapter 2, transport energy consumption has been shown

to have a significant inverse relation to destination accessibility, public transport accessibility, land use mix, intersection density and network connectivity (Ewing & Cervero, 2010). The measure of density acts as a proxy for these variables to some extent, and has also been shown to have a significant inverse relation to transport energy consumption (Newman & Kenworthy, 1999; Ewing & Cervero, 2010). Newman and Kenworthy (1999) compared overall urban density to private transport energy consumption in 37 international cities using data from 1990. Although New Zealand cities were not analysed in the study, Australian cities may be expected to have similar land use and travel patterns as major cities in both countries developed initially around the Transit city model but have since been similarly influenced by Automobile city planning regimes. Christchurch and Hamilton are more dense than the average Australian city, measured at 12 persons per hectare, but slightly less dense than Melbourne, at 15 persons per hectare, and appreciably less dense than Australia's most dense city, Sydney, at nearly 17 persons per hectare. American cities average approximately 14 persons per hectare, but range from 9.5 persons per hectare in Houston to 23.9 persons per hectare in Los Angeles. In comparison Canadian, European and Asian cities average 29, 50 and 162 persons per hectare, respectively. As decreasing density is related to increasing transport energy consumption, the conclusion that decreasing density should increase minimum energy requirements seems plausible. This would indicate that Canadian, European and Asian cities are likely to be more adaptable in the face of fuel constraints than cities in America, Australia or New Zealand.

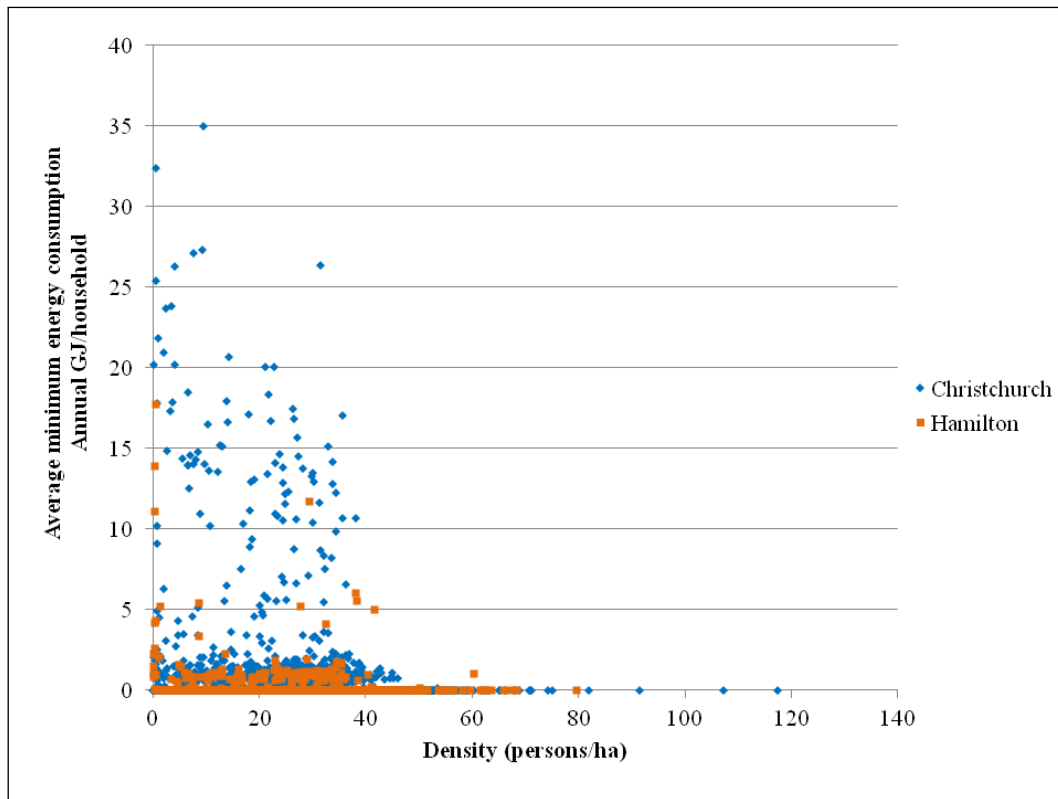
However, measures of overall urban density tend to hide important factors that might significantly influence transport energy adaptability. For example, of three cities with the same overall density, one might have a population evenly distributed across the entire urban area, while another might have dense development along transport corridors with low density development elsewhere, and a third might have an extremely dense core surrounded by low density development. Energy consumption and transport adaptability within each of these cities would vary significantly, despite the fact that they have the same overall density. The Greater Metropolitan New York region is an example of a city with a dense core surrounded by low density areas. In 1980 the density in central areas of New York was 250 persons per hectare, while in outlying areas it was 13 persons per hectare (Newman & Kenworthy, 1999). The corresponding annual fuel consumption in central areas was  $10 \frac{GJ}{person}$ , but  $60 \frac{GJ}{person}$  per person in outlying areas (Newman & Kenworthy, 1999). However, density alone does not fully describe transport energy consumption trends. When considering the entire metropolitan area, New York has a similar density to Vancouver, but approximately 50% greater private

transport energy use; while the city of Copenhagen has a slightly lower density than the Canadian city of Edmonton, but less than half the private transport energy use (Newman & Kenworthy, 1999). This indicates that overall urban density is unlikely to be a particularly useful predictor of transport energy adaptability.

Rickwood and Glazebrook (2009) explored the relation between public transport use for travel to work and density at a higher resolution, selecting the census unit area level rather than the overall city. They found increasing public transport mode share with residential density and proximity to CBDs in Australian cities. However, they also identified that the strength of these relationships lessens if more complex measures of urban form and access to public transport are introduced into the analysis. This suggests that local area density and distance from the CBD are simply useful proxies for public transport based accessibility.

An analysis of census Meshblock residential density versus average META minimum energy consumption within each Meshblock is shown in figure 6.67. The results indicate that higher density areas typically have low META minimum energy, but low residential density is not necessarily related to higher minimum energy. The factors that actually influence energy adaptability, namely destination proximity and transport network presence and level of service, typically improve as density increases, but low density is not a consistent predictor for their absence. For example, in larger cities it is entirely possible that an area may have high residential density but be distant from, and poorly connected to, many activity destinations.

It is suggested that a more effective metric for roughly estimating energy adaptability would be the geographical footprint of a city; da Silva et al. (2007) determined this factor to be a strong predictor of transport energy consumption in 27 Brazilian state capitals. This value could be more specifically represented by assessing the distance of residential areas from core activity centres, such as the CBD. Rough analysis of the results for Christchurch and Hamilton indicate that household META energy requirements become non-zero at approximately four to six kilometres from the central city, and grow with increasing distance. These values correspond approximately to the effective mode ability for cycling, which ranged from 4.8 to 5.8 km across the two cities. The proposed metric presents implications for large sprawled cities, for example, Greater Metropolitan New York, which has an urban area extending approximately 60 km from the centre in some places. This is not to imply that the entire 60 km distance is devoid of destinations or significant activity centres, but certainly large parts of this area are likely to be more than six kilometres from *significant activity* centres. By implication, many households in the Greater Metropolitan New York area



**Figure 6.67:** Average META minimum energy within census areas versus residential density

are likely to have high minimum energy requirements and thus low energy adaptability. Hence the metric of *effective radius*, defined as the radius assuming the land area of the city forms a circle and the core activity centre is centrally located, is proposed as an easily calculable estimation of energy adaptability. The effective radii of a number of international cities, including Christchurch and Hamilton for comparison, are presented in table 6.16. The measure does not directly take into account population density, but values should be viewed in the context of urban population. Increasing population for a similar size is likely to increase energy adaptability, as the destinations to service that population are more likely to be proximate. For example, Tokyo-Yokohama has a 15% larger radius than Chicago but has over four times the population, and is hence postulated to allow greater transport energy adaptability. Cities from table 6.16 that exhibit characteristics of extreme urban sprawl, and are thus likely to limit resident transport energy adaptability, include New York, Chicago, Paris, Melbourne, Brisbane, Sydney, Portland and Auckland.

**Table 6.16:** Effective radii and population for selected international cities  
(Demographia, 2012)

City	Effective radius (km)	Population (Millions)
New York	60	20
Tokyo-Yokohama	52	37
Chicago	47	9.1
Shanghai	33	21
Sao Paulo	32	20
Paris	30	11
Melbourne	26	3.5
Brisbane	24	1.8
Sydney	24	3.8
Istanbul	23	14
London	23	8.6
Portland	21	1.9
Rome	19	3.8
Auckland	13	1.3
Christchurch	7.5	0.38
Hamilton	4.7	0.15



## CHAPTER 7

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# DISCUSSION

This chapter discusses the Minimum Energy Transport Adaptability (META) methodology, reiterates the principles underlying the method, considers the assumptions behind the theoretical method, and examines the issues and assumptions applied during implementation of the method. The chapter concludes with a discussion of the specific model improvements planned for future work.

The META methodology developed in this research applies the following core principles in estimating the minimum transport energy consumption within an area:

- Activities:**
1. The closest facility for any non-employment activity is a viable destination for that activity.
  2. A number of possible employment facilities must be available, to account for labour specialisation.
  3. The current frequency of travel to activities is a necessity.

**Mode:** The lowest-energy mode within the ability of the residents is utilised for travel to each activity. The following threshold hierarchy is applied:

1. if the trip is within the resident's walking ability, it is walked;
2. if the trip is not walkable, but is within the residents' cycling ability, it is cycled;
3. if the trip is neither walkable nor cycleable, but routes are available and the trip would be within the public transport ability of the residents, the trip is made by public transport;

4. if neither active modes nor public transport are viable for the trip, it is made by private vehicle.

These principles synthesise a situation in which viable short term mode and activity travel adaptations have been adopted, although it does not currently assess the adaptation of increases in trip chaining or vehicle occupancy. Future work for the model proposes to calculate trip chaining as a spatial property and will further assess the implications of increasing vehicle occupancy, as described in section 7.4.

The theoretical META method applies the following assumptions:

1. Age is the key determinant of:
  - the particular activities carried out by an individual and the frequency of their participation in them,
  - the ability of a person to travel by different modes, and
  - the extent to which a person currently engages in trip chaining.
2. The ability of a person to use a given mode is dependent upon the travel time by that mode.
3. Modes specified by the minimum energy hierarchy are viable for the trip. This neglects the effects of weather, loads, passengers, travel perceptions, accompanying minors and emergency travel.
4. Trips to all activities are home-based, meaning they originate at the home and return once complete.
5. The adaptive response of vehicle occupancy increases is neglected; hence, modal energy intensity values for public transport and private vehicles, defined in terms of Megajoules consumed per passenger-kilometre, are constants.
6. The adaptive response of increasing trip chaining is neglected.

Furthermore, due to limitations of data availability and travel survey design characteristics, and to simplify model development, the implementation of the META method applies the following assumptions:

1. Age-dependent mode ability can be defined as the 75<sup>th</sup> percentile value of surveyed travel time for each mode, by people of the specified age group.

2. Minimum saturation values can be defined as the 25<sup>th</sup> percentile saturation value for each activity within survey activity classifications.
3. Each facility for an activity, up to the minimum saturation value for the activity, attracts an equal share of the trips to that activity.
4. Current levels of trip chaining can be calculated as a demographic property and applied to household travel patterns.
5. Demography can be assigned to households in a given census area as the average age and number of residents within the census area.

The following sections discuss the assumptions and issues around both the theoretical method and implementation of the method.

## 7.1 Methodological assumptions and issues

### 7.1.1 Age as travel determinant

The assumption of age determining activity frequency, mode ability and trip chaining appears valid. Age is obviously a key determinant of the activities which someone participates in, as children are required to attend school and adults are typically employed, and has been used to define activity patterns in previous studies. Similarly, mode ability varies with age, although to a lesser extent. The literature does not present any studies examining the ability of persons to travel by various modes. Extremely young and extremely old people typically possess lower ability to use physical modes. The variable of trip chaining similarly shows some variation with age, although this is likely related to the activities engaged in by each demographic cohort, as between the ages of 20 and 60 there is very little variation. Trip chaining is actually a property of travel behaviour and the urban form, rather than of age. Future work for the model proposes to improve the treatment of trip chaining, to correctly represent it as a spatial element and investigate its capacity as an adaptive response, as described in section 7.4. No other demographic property is likely to explain the abilities and requirements of people as concisely as age. Alternatively, neglecting the specific resident demography and using simple population averages would fail to highlight the needs and requirements of particular demographics.

### 7.1.2 Travel time definition of mode ability

The simplifying assumption that mode ability is based solely on travel time is considered to be invalid. In reality, different demographics have the ability to travel at different walking and cycling speeds. Hence, the distance covered by a given travel time will vary significantly across a population, despite the fact that the travel times vary very little. Travel time is considered to a valid basis for public transport ability, but the walking requirement at trip ends must still be considered. It is proposed that future development of the model will consider travel speed for different ages by walking and cycling in determining the mode for each trip, as described in section 7.4.

### 7.1.3 Mode viability

The assumption that a person may use a mode determined as viable for a given trip, based upon their specified ability, appears valid in light of the research intention to understand the *limits* to transport adaptation. This assumption neglects the effects of weather, loads, passengers, travel perceptions, accompaniment of minors and emergency travel. The overall method does, however, account for the varied activity requirements and modal abilities of different age groups; for example, elderly people make a greater number of medical-based trips, but also have lower ability to use active modes.

The consequences of weather, requirements of carrying loads such as groceries, and conveying passengers and minors are likely to increase minimum energy above that calculated by the method, as these factors will make active modes less viable for certain trips. The effects of travel perceptions are difficult to quantify, but are expected to lessen with greater uptake of active modes and public transport - a product of necessity rather than choice as fuel constraints worsen. As the research primarily focuses on day-to-day travel the implications of emergency travel requirements can be neglected. In reality, occasional and emergency travel will require private vehicles, further increasing the minimum energy above that calculated by the method.

### 7.1.4 Home basis of trips

The assumption of trips being home based is commonly applied in accessibility modelling (e.g., [Abley & Halden, 2012](#)). However, it fails to capture the effects of trip chaining or tours, such as conducting a shopping trip during a break at work. Improved treatment of trip chains, as described in section 7.4, will address this issue.

### 7.1.5 Vehicle occupancy

The assumption of neglecting vehicle occupancy increases is unreasonable. Increasing occupancy of private vehicles is a valid transport energy adaptation, and increasing use of public transport will decrease the energy intensity per passenger. It is suggested that further research be carried out to establish the impact of this assumption, as described in section 7.4. For example, the META minimum energy result, if utilising minimum European values for modal intensity, could be compared to the current result.

### 7.1.6 Trip chaining as an adaptive response

The methodology currently neglects increases in trip chaining as an adaptive response. Current levels of trip chaining are approximated in the implementation by assuming that trip chaining is a demographic property, as discussed in section 7.2.3. Although it may be possible to estimate increases in trip chaining using spatial techniques and activity scheduling, as discussed in section 7.4, the only existing survey data on travel adaptability indicates that there is limited capacity for this adaptation ([Watcharasukarn et al., 2012](#)). These results imply that people are already undertaking trip chaining to an optimal extent to minimise their travel time or cost. Consequently, the assumption appears valid.

## 7.2 Implementation assumptions and issues

The constant inputs of mode ability, minimum saturation and trip chaining have been estimated through various assumptions and calculated from national level household travel survey results. Activity frequency is also a constant input calculated from national level household travel survey results, however, it is a core principle of the model and no implementation assumptions have been made with regard to this characteristic. The implications regarding these inputs and their application within the model are discussed in sections 7.2.1, 7.2.2 and 7.2.3 respectively. The method of demographic assignment is discussed in section 7.2.4, the sensitivity of the model to changes in these variables is reviewed and discussed in section 7.2.5, and quality issues regarding the study area data are discussed in section 7.2.6.

### 7.2.1 Mode ability

The concept of measuring how far people *can* travel, here termed mode ability, is foreign to the literature. The model assumes that the 75<sup>th</sup> percentile of current travel by each mode represents a generalised population limit on ability. This percentile was determined arbitrarily, in absence of any quantified data or research. The mode ability is applied as a threshold in the stepwise impedance function for accessibility by each mode. Traditional accessibility models assume that impedance functions follow decay curves, such as the negative exponential or weighted logistic curves. The computational META model is capable of operating on this kind of decay function, and it is possible to calculate parameters for these functions from household travel survey data. However, such an application based upon survey results would capture the effects of *current* travel, rather than characterise the *ability* of people to travel. Future directions for development of the model include investigation of the concept of mode ability and will attempt to define functions that might represent ability, as outlined in section 7.4.

### 7.2.2 Minimum saturation values

Minimum saturation values are a correction for the grouped activity classifications typical in household travel surveys. For example, the classification of *shopping* includes travel to any facility at which goods can be purchased, and notably includes grocery stores. It is unclear how many *shopping* facilities would in fact be required for someone to satisfy their shopping need, or, if the model hypothesised a pseudo-classification scheme, how often people would travel to each of the separate shopping facilities. The idea that household travel survey results can be used in conjunction with facility data to determine how many facilities respondents did not select that were as distant in travel time from their point of origin as the facility they did select appears to be valid. Furthermore, the assumption that the 25<sup>th</sup> percentile of this value would determine the *minimum* also appears valid; for example, 25% of shopping trips in Christchurch currently forgo up to 67 shopping facilities. This assumption neglects issues regarding survey sampling and the fact that some facilities may be non-competing for the activity; for example, if shopping for books, a corner dairy or clothing store will not satisfy the activity. Future work will analyse the saturation value calculation in greater detail, and review other potential data sources, such as city-level travel surveys where available, as outlined in section 7.4.

The assumption that each located activity facility, up to the saturation value, attracts an equal share of the activity trips appears valid. In the absence of more detailed

facilities' data, which could indicate the relative size or importance of different facilities and thus allow weighting of trip attraction, the assumption provides a reasonably realistic basis for the minimum energy estimation.

### **7.2.3 Current levels of trip chaining**

The method does not assess the implications of increasing trip chaining as an adaptive response, and this assumption is discussed in section 7.1.6. Current levels of trip chaining are simply approximated in the implementation by assuming that trip chaining is a demographic property. In reality trip chaining is a spatial property of the urban form, and is largely related to destination clustering and the availability of destinations on routes. Future work will involve more detailed analysis of survey responses and relevant literature to determine an improved method of implementing current levels of trip chaining, as discussed in 7.4.

### **7.2.4 Demography assignment**

Assignment of household demography as the average age and number of residents within the census area containing those households provides a reasonable estimate, but fails to capture some critical elements of travel. Most importantly, the ability to travel by different modes varies significantly by age, but the average age within areas across a city shows much less variation. Furthermore, average ages within areas tend towards the central ages over which mode ability varies very little. An improved analysis would randomly assign the census population to households within each area, then directly apply the activity frequency and mode ability values to each person. This would better represent travel for those who require it. At present a trip to Primary school is made by someone with the mode ability of the average-aged person in the area, rather than with the ability of a 5-12 year old child, which may be significantly lower. This proposed method of demography assignment is outlined in section 7.4.

### **7.2.5 Sensitivity analysis of constant inputs**

The META model constant inputs, mode ability, activity frequency and trip chaining, are derived from travel survey results. This type of survey samples random members of a population and attempts to estimate the travel patterns of the general population. However, sampling methods can introduce uncertainties, as can estimations based upon sampled data. Although not explicitly calculated for this application, New

Zealand Household Travel Survey results when stratified to this level of detail present an uncertainty of approximately  $\pm 5\%$  (Milne et al., 2011). The minimum saturation values are calculated based upon both household travel survey results and facilities' data. As described above, travel surveys present uncertainties, but facilities' data may also contain inaccuracies, as outlined in section 7.2.6.

It is of particular interest to test the sensitivity to variations in minimum saturation value, as the values are calculated through an analysis developed by this research that utilises two different sources of potentially uncertain data. Values calculated for each city and those used in the final model are presented in tables 6.1 and 6.2, respectively. There is significant variation between the three cities for which saturation values have been analysed, with individual city values for activities as low as one eighth and as high as three times the overall values used in the model. It is possible that these variations are due to spatial factors. For example, in comparison to the more elongated profiles of Hamilton and Dunedin the relatively circular layout and unconstrained topography of Christchurch makes it easier to travel in all directions, and potential destinations are more likely to be present in many directions. Due to these factors, an equal travel time radius from a given origin in Christchurch is more likely to contain a greater number of destinations than is the case in the other cities, which may explain the higher values typically seen in Christchurch. However, sample size issues are also an important factor in ensuring validity of the results. The aim of this sensitivity analysis is to determine the possible implications of inaccuracy, and establish the priority of future work.

To test the sensitivity of the model to input parameters, six Christchurch Area Units were analysed and the model repeatedly run for various permutations of each of the input parameters. The areas were selected to capture geographic variability, as shown in figure 7.1, and a spread of minimum energy consumption, as shown by the initial results in table 7.1. The analysis tests the effect of increasing or decreasing one constant input while holding the others fixed. Each input was tested under four scaling scenarios:  $-50\%$ ,  $-5\%$ ,  $+5\%$  and  $+50\%$  of the original value. The results of the sensitivity analysis, presented as percent change relative to initial results, are shown in table 7.2.



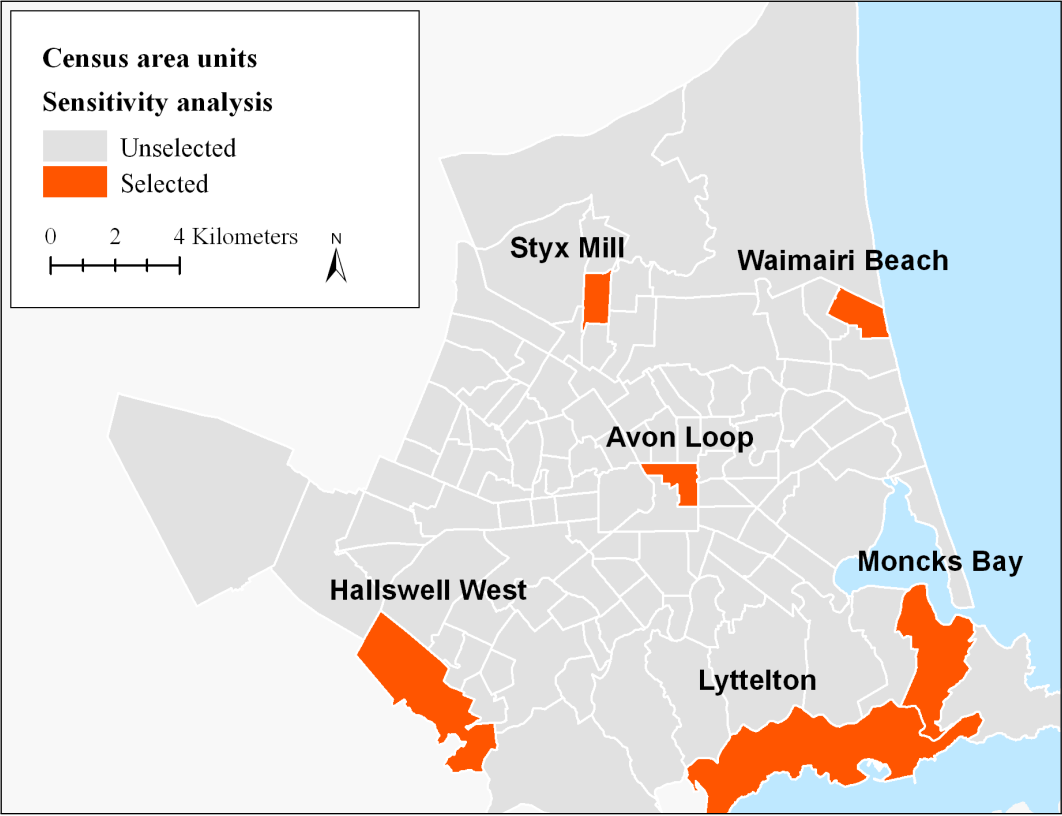


Figure 7.1: Census Area Units selected for sensitivity analysis

Table 7.1: Initial mean energy consumption values in sensitivity analysis

	Avon Loop	Styx Mill	Waimairi Beach	Moncks Bay	Halswell West	Lyttelton
Mean <i>Annual</i> $\frac{GJ}{household}$	0.0	0.8	1.8	3.8	7.2	15.9

Decreasing saturation values decrease the energy requirement, as fewer destinations are required to capture each activity. Non-linearity in the sensitivity between areas is due to differing destination proximities; a 50% increase in the number of facilities does not necessarily require 50% greater energy consumption. Changes in saturation have no effect on Avon Loop, which had an initial META energy requirement of zero, and Styx Mill, which had a low initial META energy consumption. The greatest change resulting from a decrease in saturation of 50% was a META energy decrease of 76% in Halswell West, while a 50% increase in saturation produced a 121% increase in META energy consumption for Moncks Bay. Given the scale of differences in saturation value between the three cities tested, with individual city values for activities as low as one eighth and as high as three times the overall values used in the model, ensuring the saturation values are as accurate as possible has a high priority. The differences between values for each city will be examined in further detail, and the possibility of running the model for each city utilising the saturation values for that city will be investigated. It may be possible to utilise other travel survey data sources, as well as to include more data from the New Zealand Household Travel Survey as successive years are released.

Decreasing ability to use active modes and public transport increases the energy requirement. The sensitivity between areas is severely non-linear, a result of the uneven distribution of facilities; for example, with increased mode ability, residents of one area might gain active mode access to a key shopping area with multiple facilities and employment opportunities, while residents of another area might be unable to reach any new facilities. Changes in mode ability had no effect on Avon Loop, which had an initial META energy requirement of zero. A 5% decrease in mode abilities produces no change in the META energy consumption for Styx Mill, but results in a 31% increase in META requirement for Halswell West. Conversely, a 5% increase in mode abilities reduces META energy consumption by 5% in Styx Mill, but by 36% in Halswell West. The greatest variations are seen in Waimairi Beach, with a 733% increase in META energy consumption under a 50% decrease in mode ability, and in Styx Mill a 98% reduction in META energy consumption results from a 50% increase in mode abilities. The model is highly sensitive to these variables, with META energy consumption deviations of up to 30-40% observed arising from mode ability variations of  $\pm 5\%$ , as could be expected from the NZHTS results. Furthermore, the sensitivity differences between areas are significant and non-linear. These two points indicate that uncertainties arising from use of the NZHTS should be specifically quantified, and that a more comprehensive sensitivity analysis could be included as part of the model, presenting all results with

**Table 7.2:** Sensitivity analysis results

Variable	Scenario (%)	Percent deviation from initial					
		Avon Loop	Styx Mill	Waimairi Beach	Moncks Bay	Halswell West	Lyttelton
Minimum saturation	-50	0	0	-19	-62	-76	-55
	-5	0	0	-19	-17	-14	-7
	+5	0	0	0	7	5	3
	+50	0	0	53	121	66	36
Mode ability	-50	0	198	733	310	273	63
	-5	0	0	17	22	31	17
	+5	0	-5	-12	-19	-36	-19
	+50	0	-98	-30	-95	-89	-93
Activity frequency	-50	0	-50	-50	-50	-50	-50
	-5	0	-5	-5	-5	-5	-5
	+5	0	5	5	5	5	5
	+50	0	50	50	50	50	50
Trip chaining	-50	0	12	12	12	12	12
	-5	0	1	1	1	1	1
	+5	0	-1	-1	-1	-1	-1
	+50	0	-7	-7	-7	-7	-7

uncertainties or as a range. However, the intention of the META methodology is to provide an estimate of the limits to transport adaptability, not to predict future energy consumption. Given that variations in the real human ability to travel by different modes are likely to be much greater than 5%, improvements to these details of the model seem trivial. However, representing modal ability using some form of decay function, rather than threshold values, might provide a more accurate representation of mode abilities, and might reduce model sensitivity to the variable, as detailed in section 7.4.

Both activity frequency and trip chaining have non-spatial effects on the META model, acting only to scale the modal travel requirements calculated at earlier stages, and hence output META energy consumption. As long as the same values are used for all areas to which the model is applied, the actual values are less important than the insight provided by variations between areas.

### 7.2.6 Quality of the study area inputs

Study area inputs of origins, census data, employment facilities, and transport networks are all of high quality. These data are from reputable sources and can be verified.

However, the non-employment facilities' data is derived from the *Everything from Zenbu.co.nz August 2011* community-contributed points of interest dataset, downloaded from <http://www.koordinates.com> and manually categorised into the appropriate NZHTS classifications. The data is not easily verified. It appears that some facility types are reliable as they have been consistently added by organisations; for example, education facilities have been added by the New Zealand Ministry of Education. However, other facilities have been added by business owners, customers, or interested parties and it is not clear how consistently or comprehensively this has been done. Furthermore, in terms of customers entering data, it is entirely possible that there could be a selective bias; facilities frequented by people who are computer literate and interested in contributing online may be a particular subset of all facilities. Bias could also vary throughout a city or between cities. Apart from facilities not entered, the data may also contain duplicates. However, the effects upon the model resulting from the quality of these facilities' data may be limited, due to the fact that the saturation values are calculated based upon the same data. The saturations data does not indicate the number of facilities actually forgone in selecting the destination, but the number of facilities *represented in the data* that were forgone. As long as the spatial distribution of missing destinations is even, using the same data when applying the saturation

values will effectively *cancel out* missing data. If, however, the spatial distribution of missing destinations is uneven, the results could be misleading.

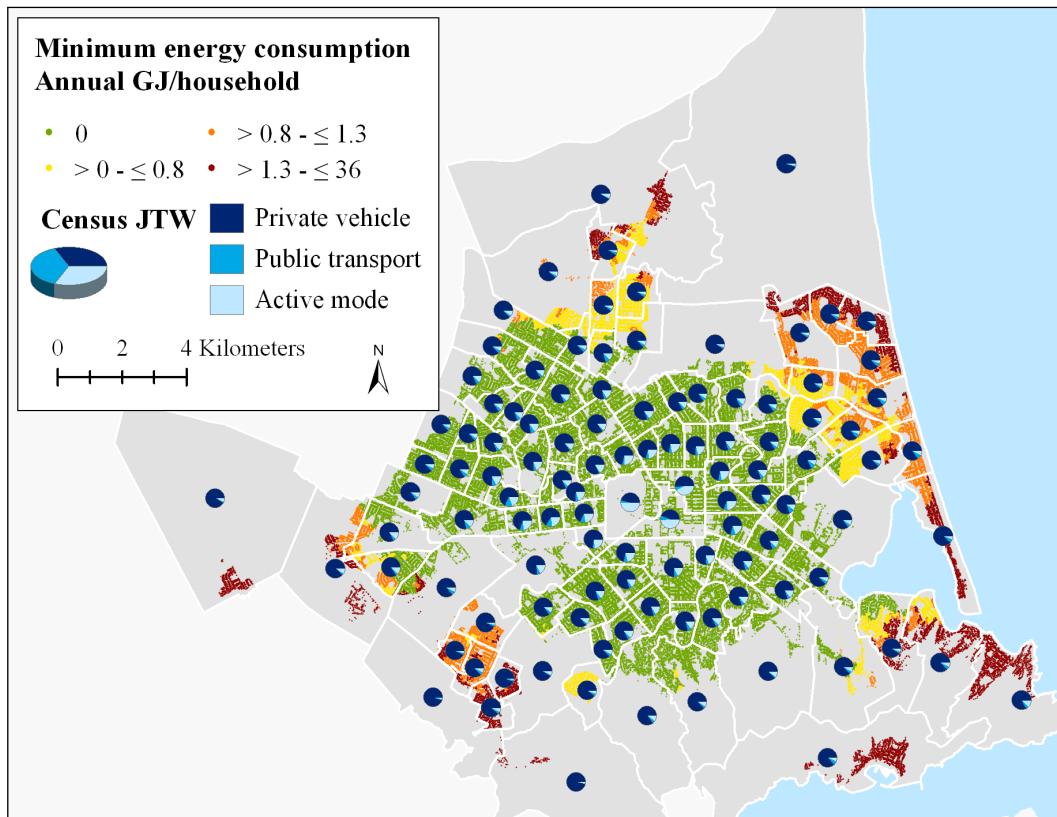
Some qualification of the extent of missing facilities data may be possible. Statistics New Zealand provides information on the number of businesses within each census unit. However, this figure includes all forms of business, many of which will not be potential activity facilities for non-employment activities. The business data can be separated into industry classifications; however, these classifications do not match the travel survey activity classifications. Under the application of some assumptions it may be possible to quantify the extent of missing data for some activities, and from this extrapolate the overall trend. This analysis is planned for future work, as outlined in section 7.4.

Although this source of facilities' data is far from ideal, it represents the best data available. Community-contributed sources are a rich and continuously growing source of information. Personal electronics, such as smart phones and GPS navigation devices, rely heavily on this data, thus it is likely to continue to grow in quality into the future.

## 7.3 Model validation

In the absence of a severe energy supply shortage, during which household travel responses are carefully monitored, it is not possible to validate the model. However, two analyses indicate that the model outputs are plausible:

- The TACA Sim survey, presented and discussed in chapter 1. The interactive survey showed that transport energy adaptations are feasible, with a 75% reduction in the number of private vehicle trips exhibited under the highest price scenario. Most of this reduction was achieved through modal shifts, but changing destinations and rearranging trips were also used.
- Comparison of the META minimum energy values with census journey to work data. The data show a high level of correlation for Christchurch, as shown in figure 7.2. Areas in which a low energy consumption was estimated by the META model also possessed higher shares of active mode travel to work, while areas with high META energy consumption are typified by nearly complete reliance on private vehicles for work travel.



**Figure 7.2:** Christchurch META minimum energy versus census Journey to Work (JTW) data

## 7.4 Future work

The current implementation of the META methodology has been developed in conjunction with Abley Transportation Consultants Limited. In consequence, the model is under continuous development, and will continue to be applied to further case studies. This section discusses the planned developments that will be integrated into the model, which will improve both methodological and implementation aspects of the analysis.

There are two aspects of the META method relating to trip chaining: increasing trip chaining as an adaptive response, and current levels of trip chaining that are applied in the minimum energy calculation. The method currently neglects increasing trip chaining as an adaptive response, and existing research supports this assumption (Watcharasukarn et al., 2012). Current trip chaining behaviour is taken into account when estimating energy consumption, but in a non-spatial manner. In reality trip chaining is a spatial property of the urban form, and is largely related to destination clustering and the availability of destinations on routes. It is proposed that further work be devoted to analysing household travel survey results in which trip chaining is

undertaken, as well as other accessibility and activity analyses in which trip chaining has been included, as reviewed in chapter 4, such as [Bowman and Ben-Akiva \(2001\)](#) and [Dong et al. \(2006\)](#). Computationally the model could account for the density and mix of destinations available, and allow trips to multiple activities to be captured when travelling to areas with high density and mix. Furthermore, if future studies of transport energy adaptability indicate this adaptation has greater potential than [Watcharasukarn et al. \(2012\)](#) observed, an approach of this form has the potential to include increases in trip chaining as an adaptive response within the model.

Further research will be carried out regarding modal energy intensity values, to account for adaptive responses of increasing private vehicle and public transport occupancy. This could include comparison of current values and model results to those in areas of high occupancy, such as Europe.

Demography will be assigned through a Monte Carlo process, in which persons drawn from the census data are randomly assigned to households within each census area. This would allow activity frequency and mode ability values to be applied directly to each person, better representing travel for those who require it. In this case, the travel speeds of different demographics by walking and cycling could be correctly represented. The improved method would allow other model enhancements, such as the accompaniment of minors and trip chaining when accompanying minors, and also has the potential to include other demographic census information, such as the number of Tertiary students actually residing within an area when considering Tertiary education travel. The improved demography assignment would require that the model be run multiple times and then averaged at the household level once convergence was achieved.

The saturation values calculation will be further investigated, and the differences between values for each city will be examined in greater detail. The possibility of running the model for each city utilising the saturation values for that city will be investigated. It may also be possible to utilise other travel survey data sources, as well as including more data from the New Zealand Household Travel Survey as successive years are released.

At present it is known that missing facilities' data may be an issue but the extent of the problem is entirely unknown. To qualify the extent of potentially missing activity facilities' data, Statistics New Zealand data for businesses will be compared to the facilities data. Under the application of some assumptions it may be possible to qualify the extent of missing data for some activities, and from this extrapolate the overall trend.

In the longer term the possibility of representing mode ability in a more advanced

fashion, rather than as a stepwise function at a specified threshold, could be investigated. This could be performed:

- through some form of decay function, which would bring the model in line with traditional accessibility models. These models assume that impedance functions follow decay curves such as the weighted logistic or negative exponential function (e.g., [Abley & Halden, 2012](#)). A curve specification would more accurately represent the differences in abilities over populations, and reduce the sensitivity of the model to changes in the mode ability variable. However, no literature exists that specifies the specific ability of people to travel by certain modes within populations, thus the development would require significant research.
- by implementing an activity-scheduling approach, such as that seen in the activity-based accessibility method of [Dong et al. \(2006\)](#), based around a constant travel time budget of approximately one hour travel per day ([Marchetti, 1994](#); [Newman & Kenworthy, 1999](#)). Areas with high accessibility by active modes would enable residents to reach their activities by active modes, while still remaining within the travel time budget; areas of lower accessibility would require greater use of faster modes to avoid violating the constant. Particularly distant locations may be completely unable to remain within the travel time budget, regardless of the travel modes utilised.

A further avenue for long term model development might be to link the method with urban microsimulation models, for example the UrbanSim model developed by [Waddell and Ulfarsson \(2004\)](#). These models attempt to predict how changes in policy will affect land use patterns and transport systems; incorporation of the META characterisation could allow the possible effects of future energy constraints to also be considered. Some combination of META and urban microsimulation might be able to represent the urban reorganisation impacts of fuel price rises, as areas of high META energy requirement become difficult to inhabit and decline in population.



## CHAPTER 8

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# CONCLUSIONS

The transport of people and goods requires energy. Historically this energy has been provided by humans, animals or wind. However, over the last few centuries the low price and almost limitless availability of fossil fuels has resulted in a near complete shift to oil as the sole source of energy for transportation. At the same time cities have grown in both population and physical size. Typical cities pre-dating fossil fuel use were around five kilometres in diameter, with population densities of 100-200 people per hectare. Modern cities can be as large as 100 kilometres in diameter with population densities averaging 10-20 people per hectare. This increase in size and decrease in density has been coupled with land use pattern changes that have separated residents from destinations and significantly increased the need for travel. In consequence, the residents of modern cities require significant amounts of energy just to meet their basic activity needs.

However, the fossil fuels underpinning modern transport systems are by their nature finite resources, and at some stage in the future their supply will decline. Numerous estimates of future oil supplies indicate with high probability that from about 2020 onward there will be ongoing diminution of oil supply. The implications of these declines for urban settlement patterns will be staggering. Of all the uses society has for oil, private transport is the most discretionary and is likely to see the largest reductions. This places city residents at risk if they are unable to adapt to meet their activity needs without energy consumption. It is crucial that the limits of transport adaptation within urban forms are understood in the face of future transport energy constraints. Two existing analysis tools assess transport energy adaptability and urban form risk related to limits upon adaptability; however, neither

tool examines the spatial distribution of adaptability limits. The Minimum Energy Transport Adaptability (META) methodology presented in this thesis characterises, for the first time, the spatial distribution of limits that the urban form places upon the ability of residents to adapt their transport energy consumption.

The results for two New Zealand cities have shown that areas on the fringes of cities have high energy requirements. This requirement is primarily a function of the distance between outlying areas and the locations at which activities can be conducted. Central areas, on the other hand, allow residents to meet their activities without any requirement for energy consumption. However, the New Zealand cities studied so far are smaller than New Zealand's largest city of Auckland and are tiny in comparison to many international cities. Sprawling automobile dependent cities such as New York, Paris and Melbourne will place ever larger energy requirements on residents, and are likely to have huge areas in which resident adaptability is severely limited.

This thesis has highlighted that future energy constraints will have significant and uneven effects on cities. It demonstrates it is imperative that planners must not only begin to consider the energy implications of urban planning decisions, but also that they must start planning for declining availability of energy for transport in the very near future. The META model, for the first time, enables the effects of future transport energy constraints to be mapped, visualised, quantified, and consequently considered in the planning process.

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## APPENDIX A

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# CASE STUDY PUBLIC TRANSPORT ROUTE MAPS

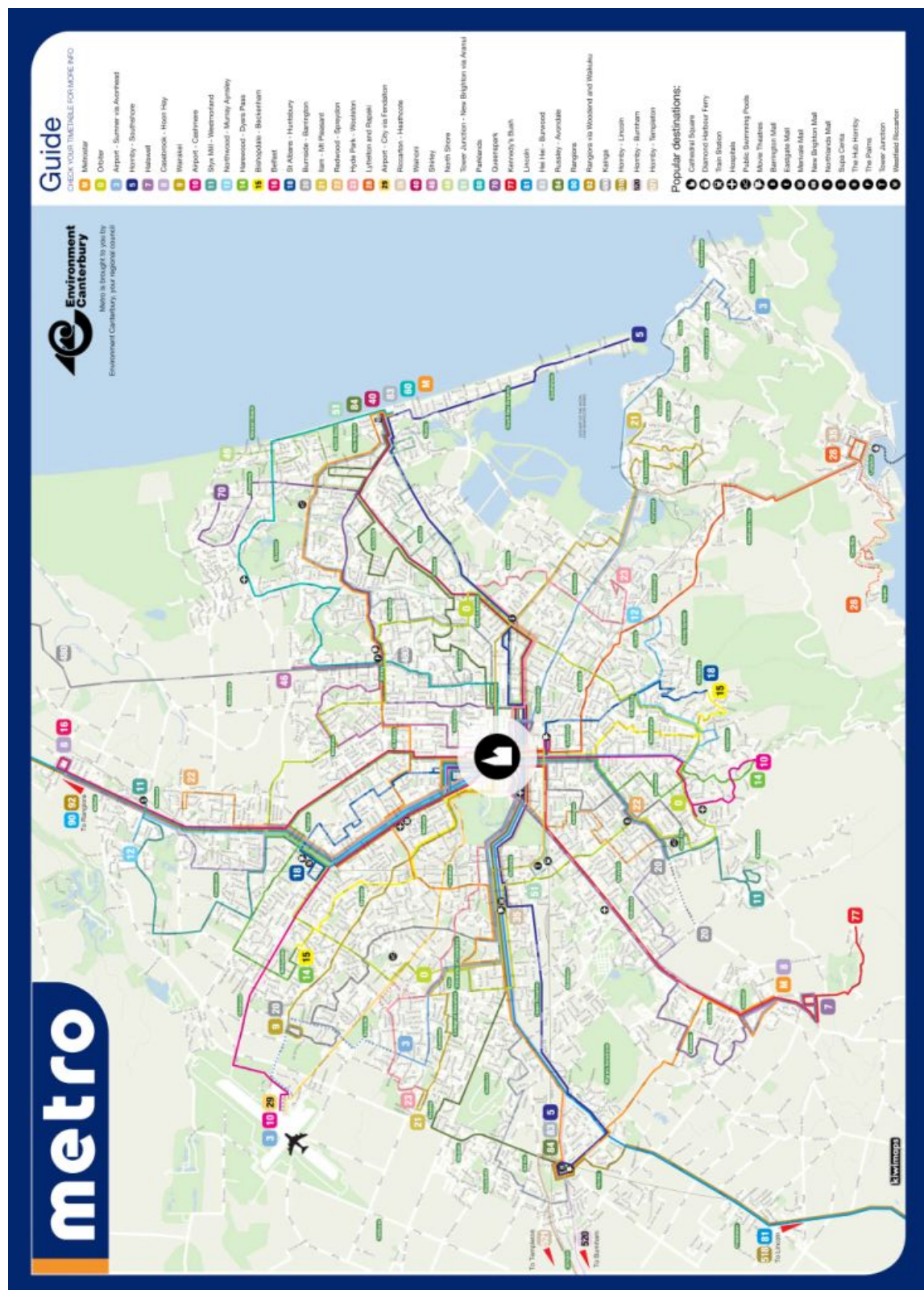
### A.1 Christchurch





Figure A.1: Christchurch inner city bus routes





## A.2 Hamilton

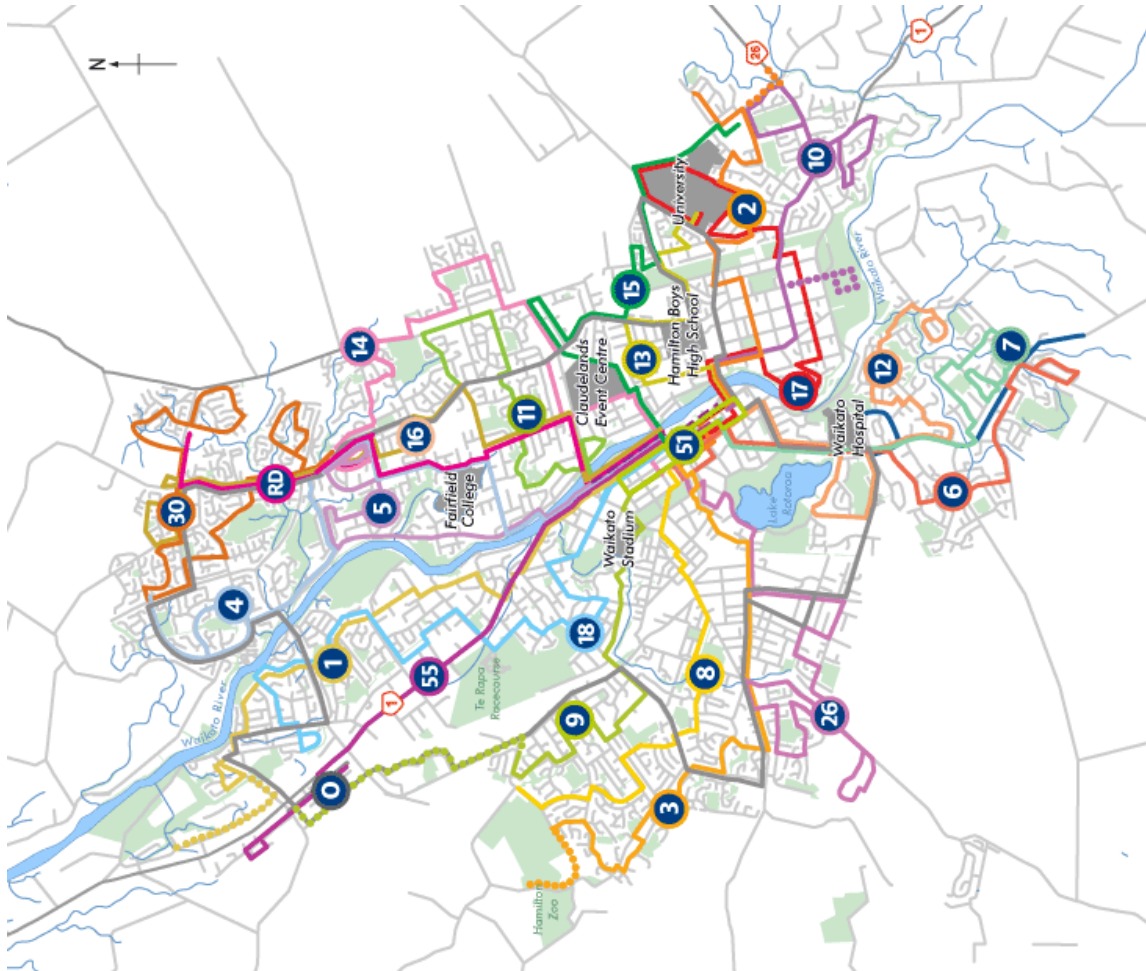


Figure A.3: Hamilton city bus routes

## APPENDIX B

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# PUBLICATIONS AND CONFERENCES

### **B.1 Peer reviewed journal papers**

#### **B.1.1 Transportation Research Record: Journal of the Transportation Research Board, No. 2242**

Paper submitted as a conference paper for the Transportation Research Board 90<sup>th</sup> Annual Meeting, January 2011, Washington D.C. Consequently accepted for publication in the Transportation Research Record: Journal of the Transportation Research Board, No. 2242.

# Quantifying Transport Energy Resilience

## Active Mode Accessibility

Stacy Rendall, Shannon Page, Femke Reitsma, Elijah Van Houten,  
and Susan Krumdieck

A reduction in the energy intensity of private transport is the least costfeasible approach to mitigate the uncertainties of future oil supplies, given the impending peak in world conventional oil production. The built environment and transport infrastructure of an urban form determine the extent to which low-impact adaptations to these constraints are possible and hence the resilience of residents to fuel price shocks and constraints. This paper introduces the concept of active mode accessibility (AMA), defined as the proportion of activities that can be reached by active modes alone, given the population demographics of the study area. AMA is characterized by the underlying geographic form of an urban area and its transport networks. High AMA means that the resident transport activity system can be served with minimal energy input; consequently resilience to fuel shocks and constraints is greater. The AMA method is based on accessibility analysis and extends the depth of the analysis with energy-based activity modeling and defines a measure of energy accessibility. The paper introduces a spatial method for calculating the AMA within a selected study area and a geographic information system-based tool for applying the method, and presents two case studies. Central Christchurch, New Zealand, gives an AMA of 100% because the city has a high density of destinations and a wide range of local facilities available for every activity. The satellite township of Rolleston gives a significantly lower AMA of 59%, principally because of a lack of local preschool and high school facilities and an insufficient diversity of destinations for some activities.

The peaking of world oil production is imminent; the International Energy Agency calculates that conventional oil production will plateau before 2030, and a meta-analysis of peak oil prediction dates undertaken by Krumdieck et al. presents a 100% probability that the peak will occur before 2030 (1, 2). Furthermore, alternative fuels will be unable to substitute for the resulting energy shortfall (1, 3). Contemporary urban forms were designed under the assumption that transport energy is cheap and readily available. Fuel price shocks and growing transport fuel prices will affect access to goods and services and will create significant flow-on social and economic costs if users cannot adapt (4–6). Energy consumption of the household travel sector is strongly related to the design and layout of the urban form (7–10). Residents will adapt their transport behavior to meet energy constraints, but there are limits to the extent of adaptation possible, which are defined by the urban form.

The hypothesis of this research is that the underlying geographic form of an urban area and its transport networks has some proportion of the resident activity transport system that can be met by active modes: walking, cycling, and public transport. Active mode accessibility (AMA) is defined as the proportion of activities that can be reached by active modes, given the population demographics of the study area. High AMA means that the resident transport activity system can be served with minimal energy input; consequently there is a greater resilience to fuel price shocks and constraints. The AMA method is based on accessibility analysis, extending the depth of the analysis with energy-based activity modeling and defining a measure of energy accessibility. A spatial method for calculating the AMA within a selected study area and a geographic information system-based tool for applying the method are introduced, and two case studies are presented.

***B.1.1.1 Review results***

Averages based on a scale from 1-Poor to 5-Excellent.

1. Objectives appropriate and clearly stated: Average=4.3
2. Methodology technically sound: Average=4.3
3. Data valid: Average=4.0
4. Conclusions valid and properly supported: Average=3.8
5. Existing work adequately described and properly referenced: Average=3.3
6. Study effort adequately described: Average=3.3
7. Overall contribution to the state-of-the-art or practice: Average=3.8
8. Originality and timeliness: Average=3.5
9. Ready for implementation by practitioners (practice-ready): Average=3.8
10. Usefulness to researchers: Average=3.5
11. Long-term value as a research reference or description of practice: Average=3.8
12. Paper organization: Average=4.3
13. Abstract clearly conveys meaning of paper: Average=4.0
14. Well written and easily understood: Average=4.5

Comments for corresponding author:

**REVIEWER 1:**

This paper is a nice application of a fairly widely used method, that is, showing how to measure local accessibility and mapping it in GIS. The contribution of the paper is not that the method is new but rather that the application is very clearly laid out so other practitioners could easily emulate it. Also, the method could be used to test resiliency but more generally it could be used to measure local accessibility to a variety of goods and services. I can even imagine it being useful for prospective residents, e.g. input what trips your household makes and see how accessible house A is in comparison to house B!

The writing is generally good but occasionally strays into marginally relevant territory. For example, it does not seem necessary to frame this in terms of peak oil, a much debated issue. The method is useful as a measurement of accessibility by active (nonmotorized) modes regardless of what side of that debate one is on.

Likewise the discussion of URBANSIMS has little to do with the paper.

## **REVIEWER 2:**

The paper presents an interesting and useful concept, the resiliency of travel by populations living in different types of urban form, in light of likely shortages/rising prices of fossil fuels. This is important for policy and planning purposes, in order to support population mobility and access in the face of expected petroleum shortfalls and price rises. This study supports the argument for denser, mixed-use development as a means for meeting societal needs while minimizing the need for fuel-based means of transportation. SPECIFIC COMMENTS: –The term ‘active modes’ needs to be defined early in the paper. It is not explained until well into page 3. Also, here it includes public transport, which requires energy external to the traveler, if not petroleum-based, then some other type of fuel. –p.3, line 41–no explanation of age-activity relationship. Source of data? Same question p. 4, lines 11 and 21–Do the census data give you trip mode, destination choices by age? You state “Age is the greatest determinant of trip frequency” as an assumption but do not cite any research or data to support this. –p.5, line 2, underlying Assumption #5 are other assumptions, i.e., that there is a jobs-housing balance and there is no skill-matching issue for labor so that the only employment destination choice factor is distance. These are fairly common assumptions adopted for model simplification but they can be invalid. Recommend mention of the risks such model simplification entails. –p. 6, lines 39-40–what is the geographic distance of this census area unit? –p. 10, lines 3-4–Inconsistency with study for which ‘active modes’ are pedestrian/bicycle only but your definition on page 3 includes public transportation.

## **REVIEWER 3:**

The introduction and the background of the paper is well researched, and the author makes a good connection between energy use and transportation. However, I would point in the background section that transit or other non-vehicle forms of transportation (i.e. segways) are not taken into account.

Its also not clear why age was chosen as the greatest determinate of trip frequencies to activities. Is there research to support this? Should proximity to a location be more

of a determinate than age?

Also, the author implied, but did not discuss, the energy saved in the trip not taken. One adaptation method is to not take a trip either because 1) costs or 2) access by other means, i.e., technology or website.

With respect to the method, the author assumes that because a person lives a certain distance from X and is a certain age Y, that they would choose to walk or bike. It's important to note that this does not take into account safety, reliability or connectivity of those modes - e.g., whether it is safe for someone to bike to a location and whether there are bike paths or low-volume streets.

Section 4.1, Discussion of the Results, jumps to a conclusion without describing to the reader how the results in each area (age, energy, activity, etc.) correspond. It would also be helpful to the reader to discuss the degrees/percentage in which Rolleston and Central City differed, and whether the numbers were in the percent of margin of error.

#### **REVIEWER 4:**

Excellent! Timely and innovative.

This is a valuable contribution to the accessibility literature and has important implications for energy, climate, the economy, equity and the environment.

More treatment of the accessibility literature would be useful – summarize leading formulations, and discuss single mode vs. multi-modal approaches. The authors' focus on neighborhood level active transportation (NMT) is very useful. The linkage with resilience/vulnerability to fuel prices is valuable. A reference to the CNT Housing + Transportation Affordability Index (<http://htaindex.cnt.org/index.php>), would be useful.

Section 2.2 Changing destinations would be another way to adapt to higher fuel prices without foregoing trips (assuming not every trip is to the most proximate destination in that category). While there might be some utility by not going to one's favorite store, there is not loss in access to fundamental services and activities in more accessible area.

Data Issues How readily available are the data used in the study (in NZ, and elsewhere if possible)? Is significant processing (e.g., 'clean up') time required or are the data in a form and format easy to use for this methodology? Did the authors' use parcel-level land use data for spatial location of residences and destinations.

P. 8. plot and note the VKT performance of the two study areas. Please note the 6-12 fold difference – very significant.

(P. 9 ironic from a health perspective that fast food can be easily reached by foot or cycle in Rolleston)

Further Research Could the model be updated to include public transport and employment? Could/will the model be applied to other (larger?) cities? It would be interesting to compare empirical travel data with the modeled minimum energy travel mode in attempt to learn which places are doing a better/worse job in achieving that potential and why.

## **B.2 Peer reviewed conference papers**

### **B.2.1 Institute of Professional Engineers New Zealand Transportation Group: 2011 Conference**



# Transport Energy Footprinting

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## ABSTRACT

*Transport Accessibility Modelling is an analytical method for understanding the ability of people to access goods, services and destinations by various transport modes. It is increasingly being used by local government bodies, both nationally and internationally, to assess the effectiveness of transport systems. This paper presents an extension of the Transport Accessibility Modelling methodology developed by Abley Transportation Consultants for the NZ Transport Agency. The new method characterises energy consumption required by residents to meet a defined Minimal Energy Activity System.*

*A new measure of Active Mode Accessibility (AMA) is introduced, defined as the proportion of Minimal Energy Activity System trips the resident population can meet by active modes or public transport. The Transport Energy Footprint is calculated as sum of trips that cannot be met by active modes. A high AMA indicates the transport activity system can be serviced with a low energy input, resulting in a greater resilience to fuel price shocks and constraints, and greater possible transport system energy efficiency. A low AMA reflects the contrary. The methodology also highlights activities that cannot be accessed by the resident population without transport energy.*

*In contrast to Milne (2011), which assesses the strategic-level travel efficiency changes of development proposals, this paper focuses on the hypothetical best-case energy efficiency of the transport system as a measure of energy resilience. The paper introduces a spatial method for calculating the AMA of a selected study area using a GIS-based tool that has been developed by the University of Canterbury Advanced Energy and Material Systems Laboratory in collaboration with Abley Transportation Consultants Limited.*

*The paper presents a case study comparing two areas within the greater Christchurch region. The Central Christchurch area results in an AMA of 100%, and a minimum petrol requirement for private vehicles of 0L/person/year because there is a high density of destinations and a wide range of local facilities available for every activity. The satellite township of Rolleston results in a significantly lower AMA of 59% and a minimum petrol requirement for private vehicles of 911L/household/year that is principally due to a lack of local pre-school and high school facilities and an insufficient diversity of destinations.*

## INTRODUCTION

The transport energy consumption of households is strongly related to the design and layout of the urban form (Cao et al., 2009, Bento et al., 2003, Frank, 2004, Sharpe, 1978). However, contemporary urban forms have been designed under the assumption that transport energy is cheap and readily available. This disconnect between rising transport fuel prices and urban form will affect access to goods and services, and may generate significant flow-on social and economic costs (Auckland City Council, 2008, Harward and Mussen, 2008, Gusdorf and Hallegatte, 2007). Obviously residents will have to adapt their transport behaviour and reduce costs when faced with energy constraints, but there are limits to the extent of possible adaptation, defined by the urban form.

The hypothesis of this research is that the underlying geographic form of an urban area has some proportion of the resident activity transport system that can be met by 'active modes'; walking, cycling or public transport. The measure of Active Mode Accessibility (AMA) is introduced and defined as the proportion of activities that can be reached by active modes, given the population demographics of the study area. A high AMA means the resident transport activity system can be serviced with minimal energy input. Consequently there is a greater resilience to fuel price shocks and constraints and therefore greater possible transport system energy efficiency. A low AMA reflects the contrary.

In contrast to Milne (2011), which assesses the strategic-level travel efficiency changes of development proposals, this paper focuses on the hypothetical best-case energy efficiency of the transport system as a measure of energy resilience. The AMA method is based upon accessibility analysis, extending the depth of the NZ Transport Agency (NZTA) methodology that was developed by Abley Transportation Consultants, with energy-based activity modelling and defining a measure of energy-accessibility. This paper introduces a spatial method for calculating the AMA within a selected study area using a GIS-based tool for applying the method and presents two case studies.

## BACKGROUND

### Transport Energy Consumption and the Urban Form

The transport energy consumption of an individual is a function of travel mode, distances to selected destinations and the frequency of travel. These are in turn dependent on individual behaviour and factors of the built environment. Although transport behaviour is complex and varied, certain links with urban form are apparent. For example, residents of highly walkable neighbourhoods (those that feature higher population density, higher network connectivity and varied land uses) tend to engage in a greater number of shorter trips, which are more easily made by active modes. As a result, they partake in approximately twice the number walking trips per week compared to residents of low walkable neighbourhoods (Cao et al., 2009, Sallis et al., 2004, Frank et al., 2005, Ewing and Cervero, 2010).

Figure 1 provides an example of the differences between a walkable and non-walkable urban form in Christchurch. The diagram was produced in ArcGIS by creating a 1.2 km network service layer around a point in two suburbs and highlighting parks and commercial destinations. The analysis does not account for the amenity or safety of the network and

facilities but provides a coarse indication of walkability. The Central City (a) has a transport network with higher connectivity, indicated by a greater effective distance coverable for the same walking time, and a much greater range and number of available destinations compared to Northwood (b). Studies show that the most influential factors relating to fuel consumption are destination proximity and the availability and practicality of alternative (non-car) modes. Both of which are complex products of population density, network connectivity and land use mix (Bento et al., 2003, Sallis et al., 2004, Frank et al., 2005, Ewing and Cervero, 2010, Gordon, 2008, Kenworthy, 2003). Figure 1 qualifies energy consumption differences between two urban forms although it does not predict current travel behaviour or quantify energy resilience.

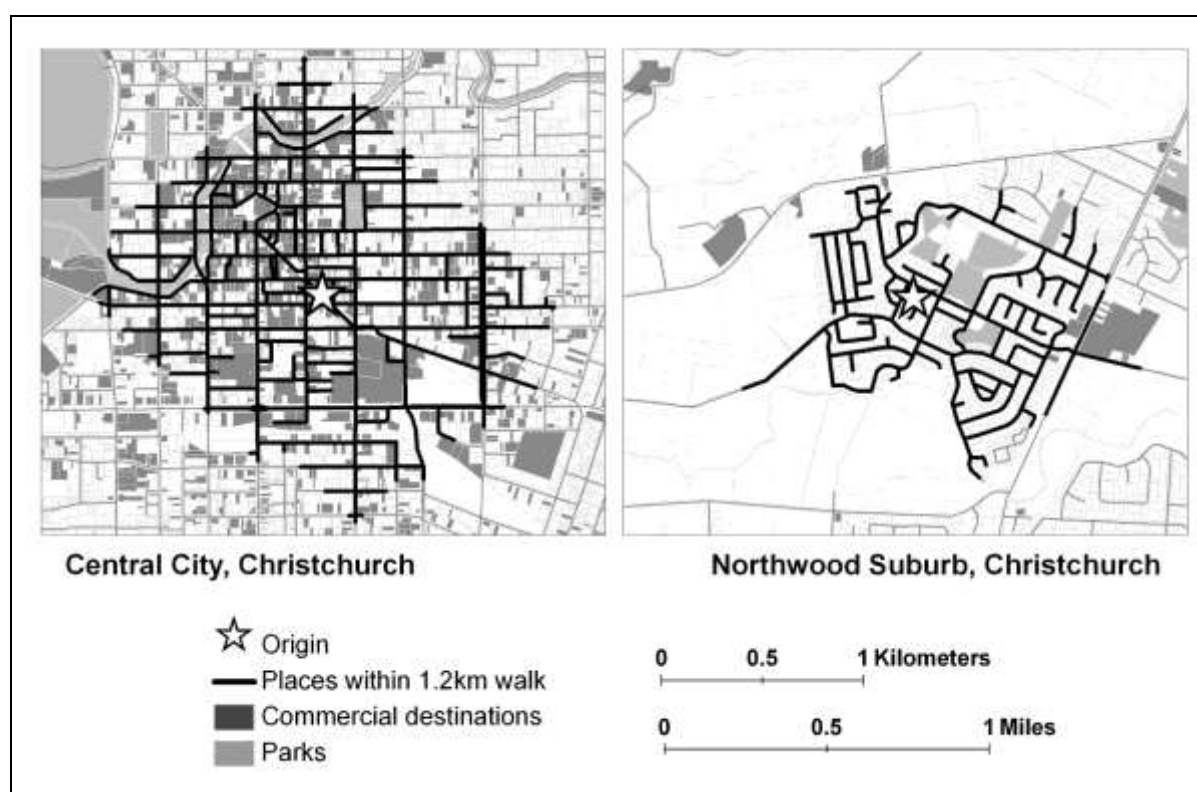


Figure 1: 15 minute (1.2km) walk along the road network in (a) the Christchurch central city and (b) Northwood suburb, Christchurch.

## Energy Efficiency of the Transport System

In general, the concept of energy efficiency refers to “using less energy to produce the same amount of services or useful output” (Patterson, 1996). For a vehicle, energy efficiency is measured as the distance that can be travelled per unit of fuel input, for example litres of petrol. More broadly, energy efficiency is defined by the ratio:

$$\frac{\text{Useful output of a process}}{\text{Energy input into a process}}$$

The transport system is a complex product of residents, land uses and transport networks. The useful output provided by this system for its users is access to activities. The energy input to this system is the sum of fuel consumed in vehicles and human energy expended through physical activity. If a standardised definition of access to activities is utilised, the energy consumption required to meet this will constitute an efficiency measure.

## Transport Adaptation and Resilience

To reduce the effects of both high fuel prices and potential fuel shortfalls, private transport users may have to modify their transport behaviour to reduce energy consumption (Krumdieck et al., 2010). There are five methods of transport adaptation: modifying travel time to avoid network peaks; chaining trips; changing fuel type; shifting to a more efficient mode; and changing destination, which includes participating in the activity without travelling (Krumdieck et al., 2010, Transportation Research Board, 1980, Chatterjee and Lyons, 2002).

If none of the adaptation methods is possible and the activity can no longer be accessed by car it must be forgone with consequent impact upon the individuals' wellbeing. The extent to which a user can adapt their transport energy consumption to reduce costs or meet constraints, without forgoing activities, is transport resilience. The extent of adaptation is limited by the nature and geography of the built environment and transport infrastructure (Chatterjee and Lyons, 2002, Transportation Research Board, 1980, Gusdorf and Hallegatte, 2007). A walkable form, such as that shown in Figure 1 (a), allows residents greater adaptability; alternative modes are more viable, due to shorter distances and higher density, and there are a large number and greater diversity of destinations available.

Short term fuel price increases tend to disproportionately disadvantage lower income households particularly where inexpensive housing is situated in low density suburbs near the urban fringe - both far from destinations and not adequately served by public transport (Transportation Research Board, 1980, Dodson and Sipe, 2005, Dodson and Sipe, 2006). However, supply disruptions which limit the availability of transport fuel, such as those experienced by western countries during the 1970's and in the United Kingdom in 2000, affect all residents. Higher income households still have a greater range of responses available such as purchasing a more efficient vehicle (Transportation Research Board, 1980, Chatterjee and Lyons, 2002, Peskin, 1980). During both historic fuel disruptions a large number of trips were forgone, including those for leisure, business and shopping activities. This indicates a lack of transport energy resilience that is partly a result of urban forms which did not allow residents to adapt, and resulted in further effects due to this lack of resilience on personal wellbeing, wider economic activity and retailers.

## Accessibility Analysis

Accessibility is defined as the ability to access goods, services, activities and destinations; or "what, and how can it be reached, from a given point in space" (Bertolini et al., 2005, Yigitcanlar et al., 2007). Figure 1 highlights some of the precepts of accessibility; the central city is more accessible by all modes, including private vehicle because there is higher connectivity and a number of destinations are within easy reach, however, the walkability analysis neither includes public transport nor distinguishes destination types so the depth of the analysis is limited. A diverse range of metrics have previously been proposed to measure accessibility including methods for locational, individual and economic perspectives (Geurs and van Wee, 2004) and indeed further metrics continue to be developed (Abley 2010). Accessibility is often contrasted with the paradigm of transport mobility which is the ability to travel further, that then attempts to increase the throughput of the transport system (Miller, 1999). Planning for accessibility typically accounts for active mode and multi-modal

options which are implicitly downplayed through the mobility analysis due to their lower distance coverage. Internationally, accessibility is increasingly becoming a policy goal; however, the criteria used in practice are often proxy measurements such as travel speed or time lost in congestion that are not particularly effective at evaluating the impacts of land-use and transport policy plans (Geurs and van Wee, 2004, Yigitcanlar et al., 2007, Straatmeier and Bertolini, 2008).

To better meet transport strategy goals, a number of GIS-based models have been developed in New Zealand and Australia that focus on measuring ‘person-based’ accessibility at the household level for a range of modes and destinations:

1. A model to quantify the social impact of policies to reduce household Carbon Dioxide emissions, embodied through changes in the level of accessibility (Mavoa, 2007).
2. The Land Use and Public Transport Accessibility Indexing (LUPTAI) model that seeks to measure how easy it is to access common destinations by walking and/or public transport (PT); it was the first model of its type to treat PT as a mode rather than a facility to be accessed (Yigitcanlar et al., 2007).
3. The comprehensive accessibility model developed by Abley Transportation Consultants Limited, a Christchurch-based company, which incorporates a flexible range of destination types and all modes including walking, cycling, PT and private vehicle modes and car parking (Abley, 2010).

However, accessibility analyses suffer from a lack of meaningful measures that are both theoretically sound and clear enough to be understandable for a variety of stakeholders and participants in the planning process (Bertolini et al., 2005, Geurs and van Wee, 2004). Additionally, the metrics often fail to distinguish the appropriate level of accessibility to be provided by the urban form. Geurs and Van Wee (Geurs and van Wee, 2004) identify the incorporation of activity-based modelling with accessibility indicators as one of their key paths for further research in the use of accessibility for the evaluation of land-use and transport strategies.

## Activity Modelling

Application of activity based approaches in modelling urban travel demand is increasing within the field of transport research, and there is a growing body of literature detailing their use in practice (Algers et al., 2005, Iacono et al., 2008). Activity Models are definitions of personal- or household-level patterns of activity; periodic trips or tours are output for a given variable such as age, income, household composition or household status (Pas, 1988, Stopher et al., 1996, Wang and Cheng, 2001, Lee et al., 2009). The advantage of activity models over traditional approaches is their greater ability to account for behaviour changes, including responses to travel demand management (TDM) policies. The use of activity-based analysis is already widespread in time use studies and travel surveys; for example, the New Zealand Household Travel Survey collects trip data in terms of the activity purpose of the trip (Ministry of Transport, 2008). Some studies have utilised age cohorts to define ‘common activities’ that are performed at a homogeneous rate within the cohort; for

example, pre-school through to secondary school education is an activity attended five times per week by children aged 3 to 17 (Saunders et al., 2008).

In this paper we propose an Active Mode Accessibility (AMA) characterization of the underlying geographic form and transport network for an urban area. AMA is defined as the proportion of activities that can be reached by active modes, including public transport, given the population demographics of the study area. A high AMA means the resident transport activity system can be serviced with minimal energy input; consequently there is a greater resilience to fuel price shocks and constraints, and greater possible transport system energy efficiency. A low AMA reflects the contrary. The AMA method is based upon accessibility analysis, extending the depth of the NZ Transport Agency (NZTA) methodology that was developed by Abley Transportation Consultants, with energy-based activity modelling and defining a measure of energy-accessibility.

## METHOD

### Theory

AMA is a behaviour-independent property of the built urban form. It is a function of population demography, distances to destinations and the viability of walking, cycling and public transport. AMA can be characterized as finely as at the single person or household level, but this study calculates it as an aggregate value at the census unit level within a defined study area. At this level AMA will: highlight activities that cannot be accessed by active modes; indicate how the transport network could be modified to increase active access; and produce a Minimum Energy Requirement for the study area by measuring the non-active travel required. The minimum energy requirement provides an energy footprint for the area, when compared to current vehicle travel.

The AMA analysis consists of three steps:

1. measuring both the travel time and distance along all networks from each residence to every activity (Accessibility Analysis using the NZTA methodology);
2. selecting, as a function of household demography and measured travel time, the mode for each destination; and
3. calculating the annual travel and fuel consumption, as a product of annual frequency, distance and mode.

AMA is the proportion of total activities that can be met by 'active modes': walking, cycling and public transport. Summing the number of trips and distances travelled by energy consuming modes, including public transport, produces a minimum energy requirement for the study area. Steps two and three of the method are based upon a *Minimum Energy Activity System*, constant over all study areas, defined by:

- Activity Model – yearly trips to activities, as defined in Table 1, by census age group.
- Mode Model – maximum travel time for each mode, by census age group.

Activity Model classifications were derived through an energy-based review of the relevant activity categories used in the New Zealand Household Travel Survey (NZHTS) and frequency sub-domains were applied to activities that possess a distinct frequency/facility split. Where relevant, facilities may occupy multiple domains. Annual trip to activity frequencies by age group are derived from the NZHTS responses for residents of urban areas.

Mode Model travel time limits for each mode and age bin are also derived from the NZHTS response data for residents of urban areas. The 90th percentile response within each age bin is utilised, after excluding responses for the trip purpose of recreational travel. Age, as opposed to income, has been selected as the defining variable for both models as maximum travel time and frequency by age reflect people's ability and requirements. Income is a discretionary modifier of basic activity patterns, which goes beyond the scope of this research.

Both Mode and Activity Model values are generated from urban area responses within the entire NZHTS dataset. These are then weighted for the demography of each study area, to represent the varying ability and activity frequency of different age groups within the area.

Data required to implement the method for each study area includes:

- Census data of population age demography;
- spatial location of residences;
- spatial location of destinations, by activity classification; and
- transport networks for all modes (walking, cycling, Public Transport and private vehicle).

## Model Structure

Assumptions:

1. Trends in basic activity patterns are determined by age group.
2. Residents are able to use the closest available facility for all destinations, except employment.
3. Employment is addressed separately by calculating the average travel time to reach a number of employment facilities. This value is currently hypothetical, but will be derived from the NZHTS and NZ Census data by measuring the number of employment opportunities, contained within Census units, that respondents travel past while accessing primary employment facilities.
4. Activity classifications contain multiple distinct destinations, this can be corrected for by assuming each destination attracts an equal share of trips to the activity.
5. All trips are assumed to be home based. However, annual travel, and hence fuel consumption, is weighted by a trip chaining factor derived from the NZHTS as the proportion of all non-home trips to the number of home trips.

Amenity and safety of routes and modes are not considered, neither is the ability to carry goods or passengers.

The model calculates then populates every household with the statistically average number of occupants of the statistically average age. The study area weighted activity model for households (*AM<sub>hh</sub>*) in the form of yearly household trips to activities, is calculated by summing the product of population count and personal activity frequency from the activity model (*AM*) per population age bin (*i*), for each activity type (*j*), and dividing by the number of households in the study area. Maximum travel times contained within the mode model (*MM*) are population weighted for each mode (*k*) by summing the product of population and age group travel time per population age bin to give a study area weighted mode model (*MM<sub>w</sub>*) that is also in time units. Network times for travel to each activity are calculated using a modified implementation of Dijkstra's algorithm (Wise, 2002, Eppstein, 2002). The output distance (*d*) is then tested against values within the population weighted mode model to determine the minimum energy mode for travel to the activity being considered. Household (*h*) distance to activity is then multiplied by the household activity weighting for each activity to give the total annual household travel to each activity. The net minimum travel demand to each activity in the study area can be determined by summing *AnnDist<sub>hj</sub>* within each activity for all households. Annual travel for each household is calculated by summing annual activity distances for all activities. Annual household travel is further summed for all households to give the net study area minimum travel demand. AMA is calculated in two ways:

1. *the AMA of four key destinations*; Primary School, High School, Grocery and Employment.
2. *the AMA of all trips*; the percentage of trips which can be made by active mode, which weights destinations of greater importance (higher trip frequency) within the study area.

A further summation of travel by energy consuming modes is also created, which, given an average fuel efficiency and study area population, can be used to determine the per capita minimum energy requirement of the study area. The Minimum Energy Activity System, which is constant over all study areas before population weighting, is a definition of energy transport level of service. Consequently, the minimum energy requirement is a measure of maximum transport system energy efficiency, weighted for the resident population. A lower per capita requirement means lower energy consumption is required to meet the same level of service, hence the transport system is more efficient. Energy footprint is calculated as minimum travel by private car compared to current travel for census units within the study area, which is derived from the national Warrant of Fitness database.

## Application

Development has started on an implementation of the method as an extension to the Accessibility Methodology developed by Abley Transportation Consultants Limited for the NZTA. The existing accessibility model calculates travel times for walking, cycling, public



transport and private vehicle modes to a flexible number of destinations. The extension of the NZTA methodology is fully described in the preceding sections and allows the model to be run at the City or Region level (depending on data availability). Further theoretical development of the project will increase the detail and sophistication of the model including the addition of a Monte Carlo simulation of population demography to enable a sensitivity analyses to be undertaken.

## RESULTS

Two areas are compared; both from the greater urban region of Christchurch city. The results presented in this section are generated within an earlier version of the model than described in the Method section, the major differences are:

- the Mode Model is based upon travel distances, not travel time; hence, modes are selected based upon travel distance;
- Employment is not considered as a destination;
- Public Transport is not included; and
- distances to destinations within activity classifications are averaged.

### Study Areas

The central city has a population of 5700, and is defined by an area within four main avenues covering nearly 7 km<sup>2</sup> over three Census Area Units as shown in Figure 2 (a). The satellite town of Rolleston as shown in Figure 2 (b) lies approximately 20km from central Christchurch, has a population of 7000, and covers a land area of 11 km<sup>2</sup>. It is comprised of one central Census Area Unit with populated areas overflowing into two neighbouring large rural Area Units; the study area includes only small sections of these adjacent units. The Rolleston road network is characterized by low connectivity cul-de-sacs while the central city is laid out in a grid pattern. Destinations were incorporated from both the study area and surroundings to avoid edge effects. For the central city a buffer radius of one census area unit, approximately 1km, was used for destination selection around populated areas to reduce edge effects. This buffer is shown in Figure 2 (a), resulting in 1755 destinations in total, equating to 0.3 destinations per capita. A wider buffer of 5km was used for Rolleston, shown in Figure 2 (b), and some destinations as far as 25km away were also included, to capture a suitable range of destinations. The Rolleston study included 103 destinations in total, equating to 0.03 destinations per capita.

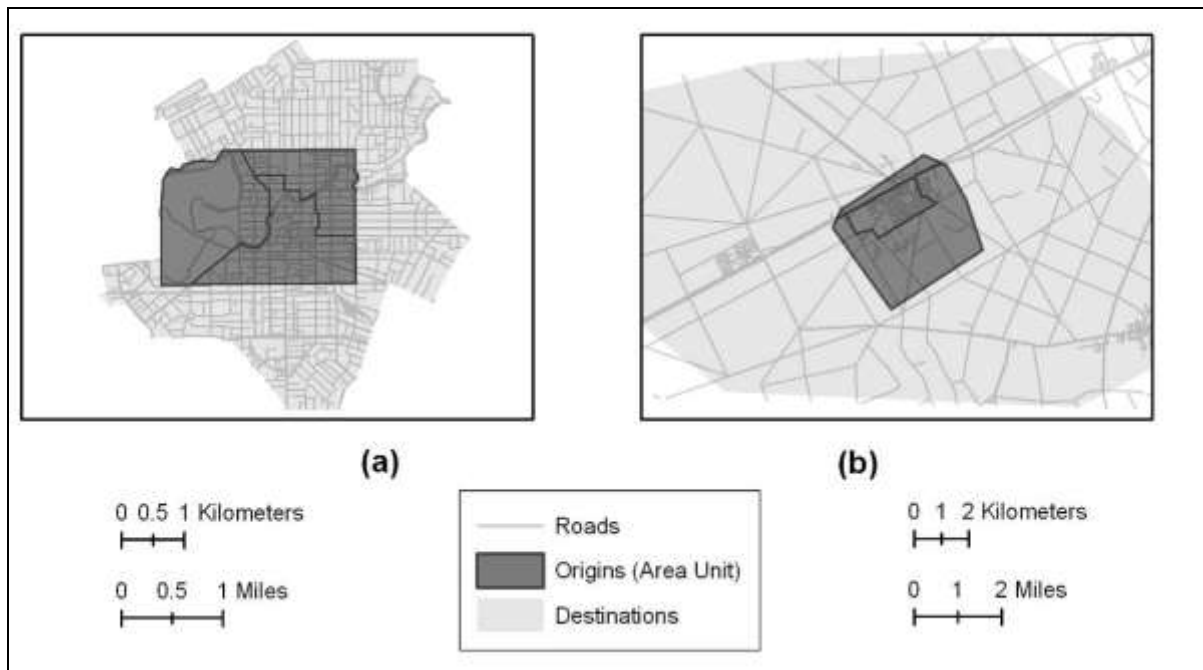


Figure 2: Study areas; central city (a) and Rolleston (b); size, layout and indication of destination selection buffers.

The population demography of each of the areas is shown in Figure 3. Rolleston has a much greater share of young families with children less than 15 years of age. The central city is largely dominated by young workers between 20 and 30 years of age, but interestingly has a slightly greater proportion of residents over 65 years than Rolleston.

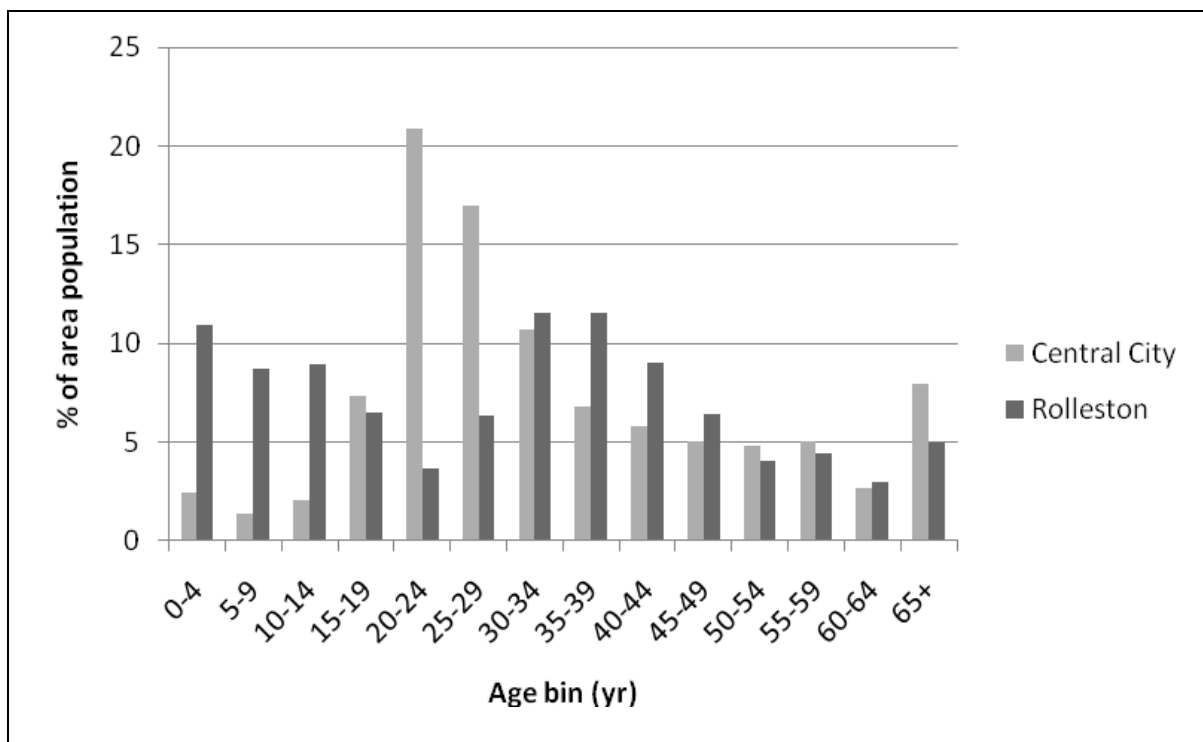


Figure 3: Relative population demography of the two study areas.

After weighting the age bin travel distances shown in Table 1 by the demography data in Figure 3, the average cycling ability for a resident in the central city is 6.7km and 5.8km in Rolleston. Walking abilities are 2.2km and 1.9km, respectively.

Table 1: Age bin travel distance by mode (before area demography weighting).

	0-4	5-9	10-14	15-19	20-24	25-29	30-34	35-39	40-44	45-49	50-54	55-59	60-64	65+
<b>Walk</b>	0	1.3	2.2	2.6	2.4	2.4	2.1	2.2	1.9	1.6	2.4	2.2	1.8	2.2
<b>Bicycle</b>	0	2.0	4.4	4.6	7.7	7.8	7.7	8.0	7.9	7.9	7.9	8.0	5.0	3.5

## Model Results

Accessibility model results are displayed as the minimum energy mode required to access a number of activities; activities with frequency splits have been averaged. Almost all residents of the central city can access destinations via walking, as shown in Figure 4.

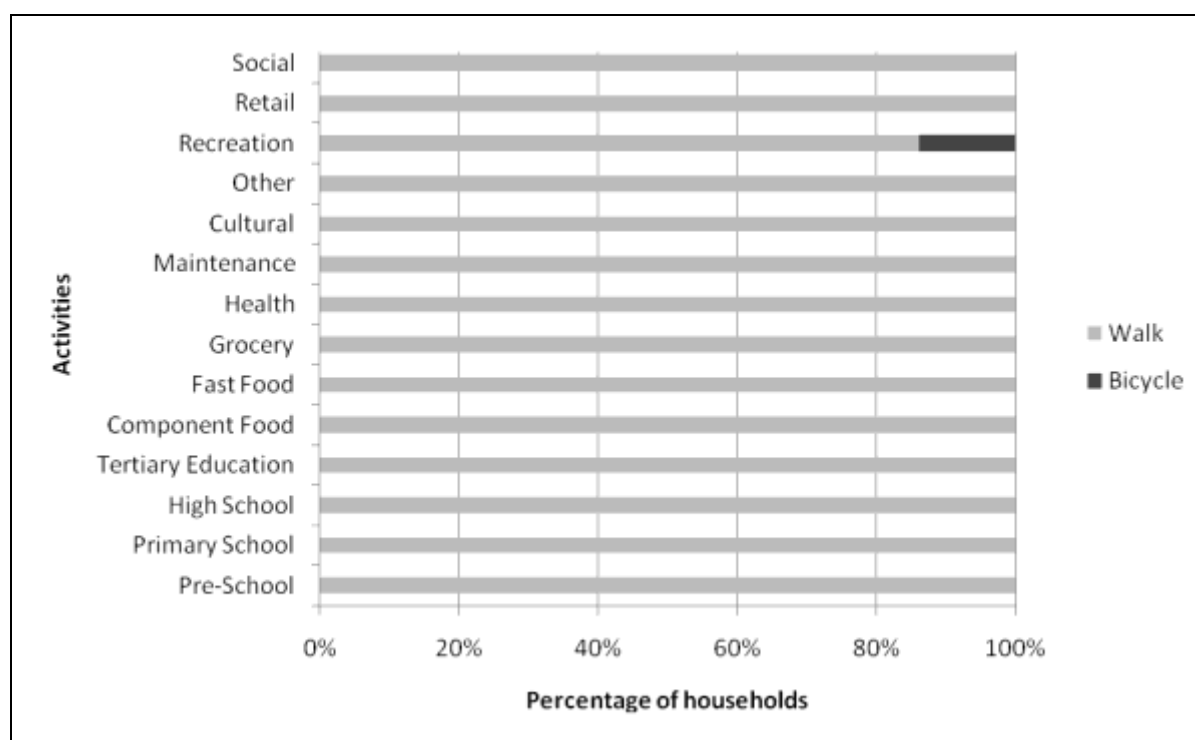


Figure 4: Minimum energy travel mode to capture activity for the central city.

Minimum energy travel mode is more varied in Rolleston, with a significant amount of car travel required as shown in Figure 5. Furthermore, the lack of diversity in local facilities within activity classifications, such as recreation, results in an average distance for many activities that is too great for active modes.

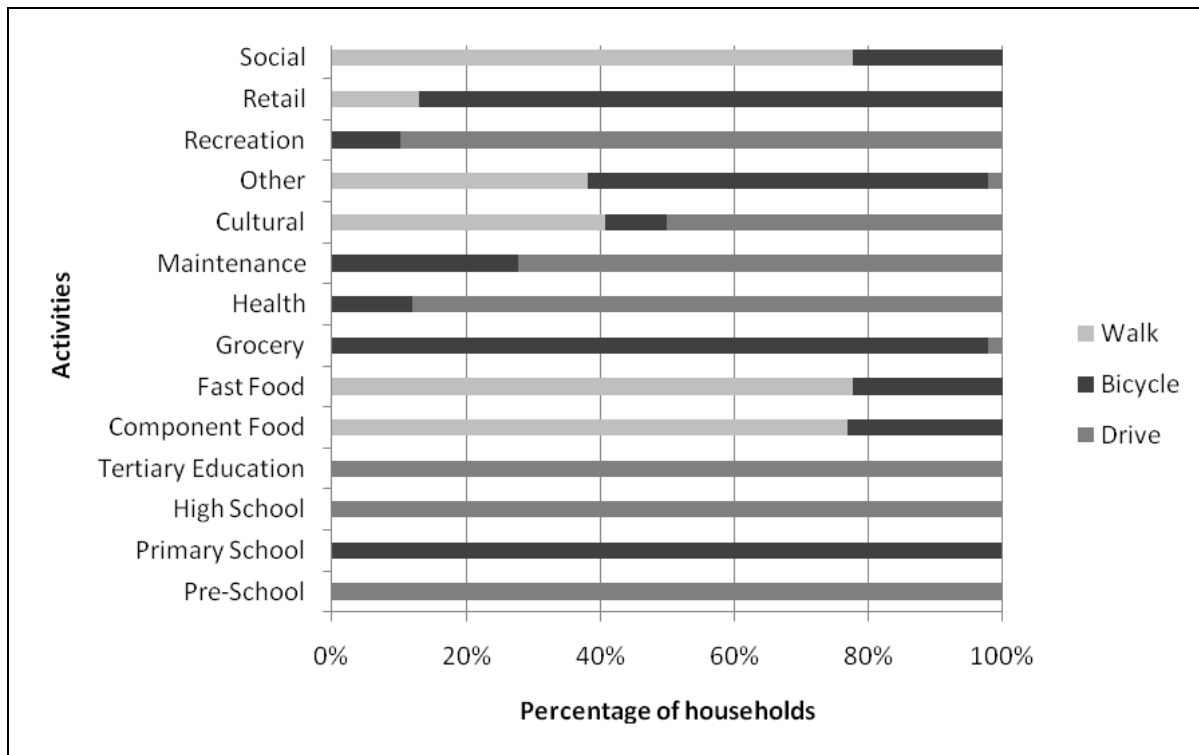


Figure 5: Minimum energy travel mode to capture activity for Rolleston.

Activity model results for each study area show that Rolleston residents are required to travel further than residents in the central city, the quantity of this additional travel is significant as shown in Figure 6. This figure shows  $AnnDist_i$ , the annual minimum household travel distance required for the activities. Given there are fewer destinations in Rolleston and road networks are not well connected, a greater amount of travel is required to reach activities. Furthermore, the greater number of children in Rolleston further increases the relative frequency with which education facilities are required to be accessed.

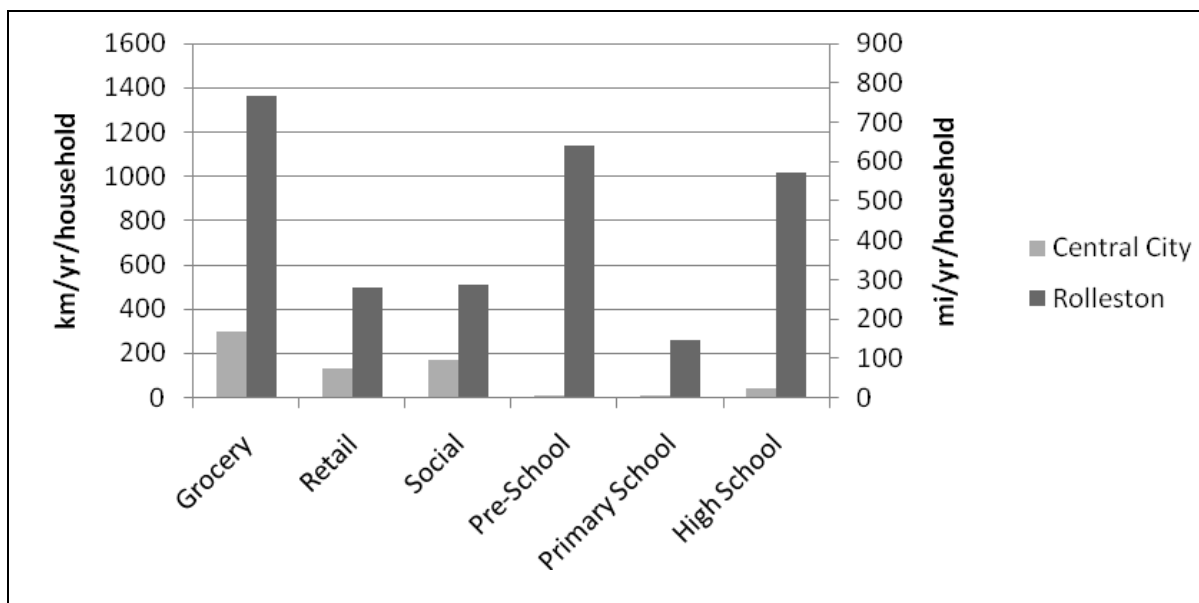


Figure 6: Annual minimum household travel demand for selected activities.

The range of net minimum household travel demand,  $SumAnnDist_h$ , for the central\_city is 1,100 to 2,500 km/household/year, while the average is 1,700 km/household/yr. This corresponds to a fuel requirement of 170 L/household/yr, or a cost of 340 \$/household/yr at current prices, if all made by private vehicle. Rolleston has a much higher range of minimum household travel demand; from 14,000 to 22,000 km/household/yr. This 8 to 12 fold increase is a result of the lack of proximate activity destinations, particularly pre-school and high school facilities, and the high proportion of school age children in Rolleston. The average minimum travel is 16,000 km/household/yr in Rolleston, corresponding to an average annual fuel requirement of 1,600 L/household/yr, a cost of 3,200 \$/household/yr.

Within the central city both the AMA to key activities (Primary and High School, and Grocery shopping) and the AMA of trips are 100%, all activities can be reached by active modes alone. This indicates the resident activity system *could* function without any transport energy inputs; thus the minimum vehicle kilometres travelled (VKT) and fuel consumption are both zero and therefore zero cost. In Rolleston, the AMA to key activities is 66% and AMA of trips is 59%; fewer activities can be accessed by the resident population using active modes. There is a minimum VKT of 9,100 km/household/year and a minimum petrol requirement of 911 L/household/year that equates to about 1,800 \$/household/year.

## Discussion of results

The AMA method has revealed a significant quantitative difference in the resilience of the two urban forms. The results show that the satellite town of Rolleston has a much lower AMA than the Central City, having no pre-schools or high school, but a greater proportion of families with young children, and an insufficient diversity of other facilities. Consequently, Rolleston also has a higher minimum energy requirement. Notably, it is not the distribution of facilities within Rolleston that contribute to its low AMA, but the lack of local facilities for certain activities.

## **CONCLUSIONS**

Urban form, transportation networks and travel behaviour are determinants of transport energy demand. The resiliency of transport activity systems to fuel price shocks and constraints has not been quantified before but it has historically been considered low for some contemporary urban forms.

This paper introduces Active Mode Accessibility (AMA) as a measure of the fuel resilience for a community with certain age, population and urban form characteristics. This novel method provides an understanding of, and empirically measures, transportation resilience and can be implemented using GIS and census data. The results represent a matching of the resident population demographics with the local accessibility of activity destinations. The AMA calculation introduced in this paper contributes both an important new understanding to future transport and land-use planning and quantifiable measures for maximum possible transport system energy efficiency and energy resilience.

The results of the two case studies investigated within this paper indicate some of the valuable outputs of this tool to better understand the factors that contribute to both transport resilience and vulnerability. The case study identified that access to education for children was particularly limited for the young families living in the satellite community of Rolleston. As both study areas are expected to significantly increase in population in the near future, these findings are valuable for future planning within the context of fuel constraints.

This new tool builds upon the work Abley Transportation Consultants has previously undertaken for the NZ Transport Agency. The further development of the AMA methodology and the ability to assess communities of different demographics yet similar urban forms provides practitioners with the ability to better understand planning applications and the effects of land use changes.

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### ***B.2.1.1 Review results***

#### **Abstract**

“The Transport Energy Footprint is calculated as a product of the trips that cannot be met by active modes.” Where a “product” is “calculated” it requires the values of two or more attributes that are multiplied together. Some amendment is necessary.

#### **Energy Efficiency of the Transport System**

The definition of energy efficiency has “Useful output of a process” on the top line of the equation and this is described below as “access to activities” The energy efficiency, as you have stated, is a ratio; it must therefore have something on the top line that is measureable in energy units to be comparable with the bottom line “Energy into a process” Some alteration or explanation is required.

#### **Active Mode Accessibility(AMA)**

The term travel impedance has been coined without sufficient commentary or definition. As part of the AMA analysis the paper refers to travel impedance for the first time with reference to “Accessibility Analysis using the NZTA methodology”. Readers of this paper can not be expected to be familiar with travel impedance, from that reference. Further on the paper defines impedance “as the 90th percentile response in each age bin, excluding responses for the trip purpose of recreational travel.” This is quite confusing, and the concept of travel impedance is of key importance in the modelling. In respect of the response in each age bin, is this separately determined for each study area? The paper states that transport networks are one of the sources of data required to evaluate AMA. Does the analysis include separate networks for walking and cycling?

#### **Model Structure**

The first assumption states that “trends in basic activity patterns are largely determined by age group.” Is it correct that this is “largely” determined by age, or should this be “wholly.” If largely is correct, what other patterns are used, and in what circumstances? The second assumption states that “residents are able to use the closest available facility for most destinations.” Why “most.” Under what circumstances are other destinations used. In an earlier section the paper discusses “well being” as being negatively affected wherever a trip by car has to be forgone. Will not well being

also be affected by modelling that includes for most (or all) trips being made to the closest available facility? Does this not constrain residents to use the nearest medical centre, hairdresser, supermarket, or school whereas none of these may be the preferred facility? In the third assumption, the selection of employment facilities to be used in the modelling, requires further explanation and validation. In the fourth assumption should “destination types” be more correctly stated simply as “destinations” that are relevant to each activity. By averaging distances the more distant destinations would be expected to have the effect of removing recognition of some or many of the shorter trips that could be undertaken by active modes. What limitations are used in establishing destinations outside of the study area? The fifth assumption requires some further explanation. How does the modelling deal with trips that include transportation of goods that cannot be carried on foot or by bicycle? For instance, grocery shopping. The results show this as all being achievable by bicycle in Rolleston and on foot in the central city.

## Results

The results do not include any details of the travel impedances used. The results could be usefully supported by the inclusion of a table showing walking and cycling impedances for each age bin (or a matrix if travel impedance is also dependent on activity). The results do not show the VKT and fuel consumption for the trips that where active modes that are assumed to replace vehicular trips. This would provide a better appreciation of the benefits of maximising use of active modes. The comment under Figure 5 “This is maybe not unexpected but..” should be re-written more concisely.

### **B.2.2 Institute of Professional Engineers New Zealand Transportation Group: 2012 Conference**

## THE PATH TO DELIVERING ENERGY RESILIENCE: MEASURING TRANSPORT CHOICE

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### ABSTRACT

Accessibility modelling is an analytical method for understanding the ability of people to access services. It is increasingly being used by decision makers seeking a better way to measure the integration of land use and transport.

This paper presents an extension of the NZ Transport Agency accessibility modelling methodology developed by Abley Transportation Consultants. The extended methodology allows the calculation of the potential minimum energy consumption required by households within an urban form, and introduces a number of useful metrics. The minimum potential is a geographic and demographic, not behavioural, measure that assesses the inherent potential for residents to choose active modes. A low potential indicates the resident transport activity system can be serviced with a low energy input and hence the community has greater resilience to fuel price shocks and supply constraints. A high potential reflects the contrary. The potential is most usefully presented as a minimum percentage of household income spent on transport; including both private vehicle and public transport.

This paper introduces the enhanced accessibility methodology and presents a case study of Christchurch city. The case study results will interest those practitioners interested in the effects of community resilience when dealing with reduced oil consumption, and those seeking better ways to identify at risk communities and test various interventions.

## INTRODUCTION

The transport energy consumption of households is strongly related to the design and layout of the urban form (Cao, Mokhtarian, & Handy, 2009; Frank, 2004). However, as contemporary urban forms have been designed under the assumption that transport energy is cheap and readily available, the disconnect between rising transport fuel prices and urban form will place pressure on travel behaviour to reduce energy consumption. This may affect access to goods and services, and may generate significant flow-on social and economic costs (Auckland City Council, 2008; Harward and Mussen, 2008).

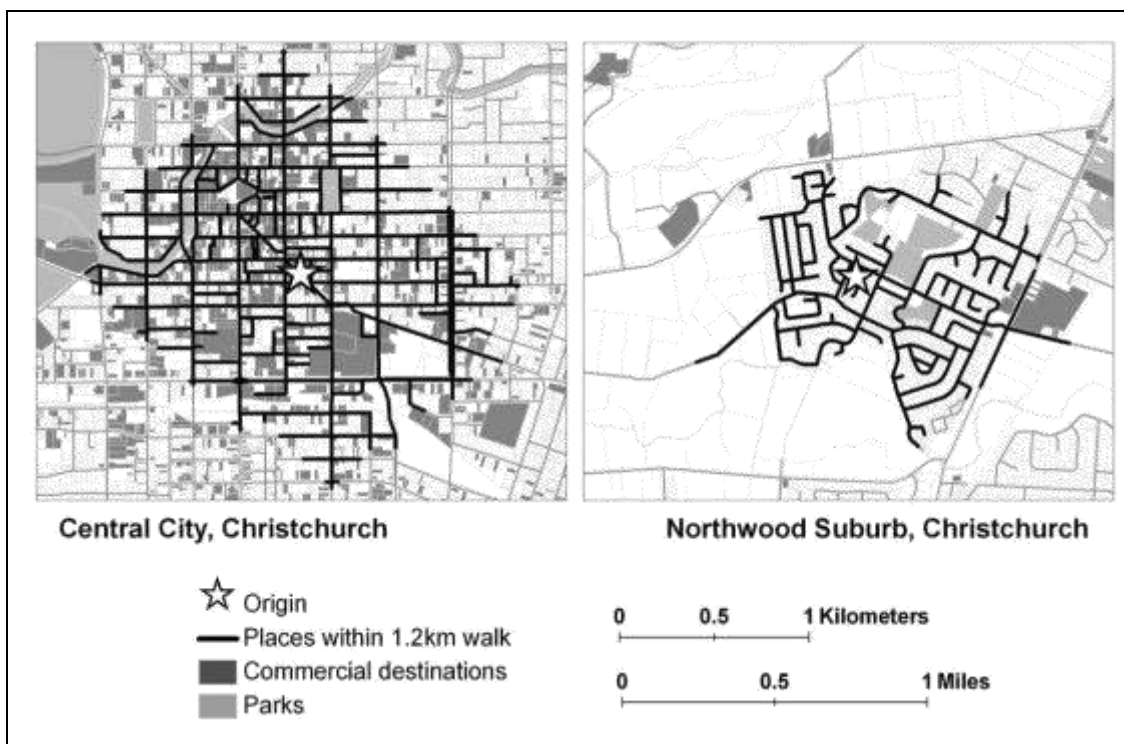
Accessibility modelling is an analytical method for understanding the geographic ability of people to access goods, services and destinations. It is increasingly being used by decision makers to better understand the integration of land use and transport, and incorporate this into transport planning. In this paper the NZ Transport Agency accessibility modelling methodology developed by Abley Transportation Consultants is extended through the application of mode-ability and activity models which use New Zealand Household Travel Survey data. The extended methodology is based upon the concept of potential minimum energy consumption for private transport that is required by households within an urban form, and introduces a range of new metrics.

## BACKGROUND

### Transport Energy Consumption and the Urban Form

The transport energy consumption of an individual is a function of behaviour, technology, travel mode, distances to selected destinations and the frequency of travel. These are in turn dependent on individual preferences, economic decisions and factors of urban form. Although transport behaviour is complex and varied, certain links with urban form are apparent. For example, residents of highly walkable neighbourhoods (those that feature higher population density, higher network connectivity and varied land uses) tend to engage in a greater number of shorter trips, which are more easily made by active modes (Cao et al., 2009; Ewing and Cervero, 2010). As a result, they partake in approximately twice the number walking trips per week compared to residents of low walkable neighbourhoods (Sallis, Frank, Saelens, & Kraft, 2004). Studies investigating urban form links to obesity, such as that undertaken by Frank, Saelens, Powell and Chapman (2007), have shown that people who prefer walking as a transport mode will intentionally choose to live in walkable neighbourhoods. Despite this self-selection factor, residents of walkable urban forms still have the option of choosing to use private vehicles for all trips.

The difference between a walkable and non-walkable urban form within Christchurch (prior to the recent earthquakes), are shown in **Figure 1**. The diagram was produced in ArcGIS by creating a 1.2 km network service layer around a point in two suburbs and highlighting parks and commercial destinations. The analysis does not account for the amenity or safety of the network and facilities.



**Figure 1: 15 minute (1.2km) walk along the road network in (a) the Christchurch central city and (b) Northwood suburb, Christchurch.**

The analysis shown in Figure 1 highlights that the Central City (a) has a transport network with higher connectivity, indicated by a greater effective distance coverable for the same walking time, and a much greater range and number of available destinations compared to Northwood (b). Studies show that the most influential factors relating to fuel consumption are destination proximity and the availability and practicality of alternative (non-car) modes (Kenworthy, 2003). Proximity and mode practicality are complex products of population density, network connectivity and land use mix (Bento, Cropper, Mobarak, & Vinha, 2003). Although Figure 1 shows a qualitative analysis of the potential fuel consumption differences between the two urban forms, through destination proximity analysis, it only indicates possible energy resilience for the particular origin examined.

### Modelling Accessibility

Accessibility is a measure of transport potential; essentially it acknowledges the availability of opportunity within the transport network, and attempts to understand what people 'could' do. In comparison, traditional Transport Modelling, which focuses on automobile mobility, attempts to forecast what people 'would' do, and typically does not recognise other travel modes or take account of what people 'can not' do (Abley, 2010). Accessibility measurement accounts for people that are traditionally transport disadvantaged and provides a better accounting of the long term transport sustainability implications. Although there are currently no national frameworks for measuring accessibility in either Australia or New Zealand, both countries are very supportive of improving accessibility at the national level (Abley, 2010).

### Activity Modelling

Application of activity based approaches in modelling urban travel demand is increasing within the field of transport research, and there is a growing body of literature detailing their use in practice (Algers, Eliasson, & Mattson, 2005; Iacono, Levinson, & El-Geneidy, 2008). Activity models are definitions of personal- or household-level patterns of activity; periodic trips are output for a given variable such as age, income, household composition or

household status (Wang and Cheng, 2001; Lee, Washington, & Frank, 2009). The advantage of activity models over traditional approaches is their greater ability to account for behaviour changes, including responses to travel demand management (TDM) policies. The use of activity-based analysis is already widespread in time-use studies and travel surveys; for example, the New Zealand Household Travel Survey collects trip data in terms of the activity purpose of the trip (Ministry of Transport, 2008). Some studies have utilised age cohorts to define 'common activities' that are performed at a homogeneous rate within the cohort; for example, pre-school through to secondary school education is an activity attended five times per week by children aged 3 to 17 (Saunders, Kuhnimhof, Chlond, & Da Silva, 2008).

This research introduces the methodology for calculating the potential minimum energy consumption of households within an urban form. The minimum energy potential is a geographic and demographic, not behavioural, measure that assesses the inherent potential for residents to choose active modes. A low potential indicates the resident transport activity system can be serviced with a low energy input and hence the community has greater resilience to fuel price shocks and supply constraints. A high potential reflects the contrary. The potential is most usefully presented as a minimum percentage of household income spent on transport; including both private vehicle and public transport. The method is based upon accessibility analysis, extending the depth of the NZ Transport Agency (NZTA) model methodology that was developed by Abley Transportation Consultants.

## **METHOD**

### **Accessibility Model**

Commensurate with New Zealand's policy support for improving accessibility, and the previous experience of Abley Transportation Consultants at developing measurement techniques, the New Zealand Transport Agency commissioned Abley Transportation Consultants to develop a methodology to assess the accessibility of a neighbourhood in May 2007. This methodology has been implemented within ArcGIS ModelBuilder, and calculates an accessibility score for access to eight core land use activities, along Walking, Cycling, Public Transport and Private Vehicle networks. Two types of Accessibility indicators are calculated at the household or meshblock level: a Threshold Indicator, which is a binary output answering a question such as 'can a doctor be reached within 30 minutes of travel by public transport?'; and a Continuous Indicator, which maps the percentage of a population with access to a destination type. Both indicators utilise Deterrence Functions to determine the rate at which destinations further away are assigned less weight in determining the accessibility result. The methodology described above has since been applied to numerous case studies, including the Gisborne District and Christchurch City.

### **Minimum Energy Potential**

The minimum energy potential extends the Accessibility modelling method described above, by calculating 'minimum energy' modes for household-destination trips and applying annual frequencies for household-destination trips. The combination of these two functions forms a minimum energy activity system. It assumes, for each destination trip, that a household selects the mode with the lowest possible energy consumption (within the ability of its residents) and utilises the closest facilities available. The minimum energy activity system is an 'energy-ideal' theoretical behaviour construct; although this behaviour is unlikely to be met in reality, the presence or absence of ability to fit this behaviour is a powerful indicator of energy resilience. Although possible that individuals or households could willingly travel further by active modes or public transport than is defined by the model, this will only act to increase energy resilience. The minimum energy activity system is applied at the household level, and is defined by the age of the residents under the assumption that each household is typical within its census collection area.

Values used in the minimum energy activity system are derived from the responses of residents of Major Urban Areas within the New Zealand Household Travel Survey (NZHTS) dataset, and are categorised into New Zealand census age groupings. Mode ability is calculated as the 75th percentile travel time for each age group. For example, the calculated values for a 20-24 year old person are shown in **Table 1**. The mode used by a household in making a trip is selected by the model as the lowest energy mode determined through the application of a hierarchy, as outlined in **Table 2**.

**Table 1: Mode ability for 20-24 year old person**

Mode	Mode ability [min] (20-24 yr old)
Walk	30
Bicycle	30
Public transport	40

**Table 2: Mode selection hierarchy based upon travel time (T) to an activity**

Energy rank (low to high)	Logical process	Selected mode
I	$T \leq Time_{Walk}$	Walk
II	$Time_{Walk} < T \leq Time_{Cycle}$	Cycle
III	$Time_{Cycle} < T \leq Time_{PublicTransport}$	Public Transport
IV	$Time_{PublicTransport} < T$	Private Vehicle

Activity frequencies are calculated assuming that the average activity frequency of respondents within the age group is typical. Activities are broadly defined as fitting into one of ten classifications, defined by the NZHTS with educational activities broken out by age group, as shown in **Table 3**. This table includes, as an example, the calculated (average) trip frequencies for a 20-24 year old person to each of the different activities.

Each NZHTS activity classification contains multiple distinct facility types; for example, 'Shopping' includes facilities such as supermarkets, book stores, chemists, clothing stores and so on. Consequently, a saturation value is used within the model that accounts for the effect of this classification. An ideal travel survey would capture travel information to every distinct type of activity, with the result that the model would only have to locate the closest single destination for each activity. The Saturation Value is defined as number of potential activity facilities that were forgone (within a radius of equal travel time) when selecting the actual destination for the activity; the Minimum Saturation Value is the 25<sup>th</sup> percentile of these values for travel to each activity. The values are calculated using the real facility locations and the NZHTS responses for travel to each activity; Minimum Saturation Values calculated for Christchurch are shown in Table 3.

**Table 3: Model activity classifications, annual frequency and Saturation Values**

Activity classification	Annual trip frequency (20-24 yr old)	Minimum Saturation Value
Preschool	0	3
Primary/Intermediate School	0	3
High School	0	2
Tertiary Education	57	3
Shopping	180	68

Activity classification	Annual trip frequency (20-24 yr old)	Minimum Saturation Value
Medical/Dental	8	10
Social Visits	240	9
Personal Business and Services	76	24
Recreation	65	1
Employment (jobs)	180	6,760

Applying the minimal energy activity system to an urban form generates a wide range of metrics, including: the specification of the minimum potential energy consumption; overall accessibility for all travel by active modes and public transport; inability to access destinations by active modes and public transport. Of these potential measures, three understandable and communicable metrics have been selected:

- **Active mode accessibility (AMA):** the percentage of four key destinations that can be accessed entirely by active modes. The key destinations are defined to be Primary/Intermediate School, High School, Shopping and Employment.
- **Public transport mode accessibility (PTMA):** the percentage of the same key four destinations that can be accessed if public transport is used as well as active modes.

**Minimum travel spend as a percent of household income:** the sum of fuel and fare costs, accounting for travel by public transport and private vehicle to all ten activities.

Both AMA and PTMA are calculated by the model once modes have been assigned to household-destination trips. AMA indicates the extent to which the resident transport activity system can be met by active modes. A high value implies the residents can engage in their activities with a low energy input, and hence the community has greater resilience to fuel price shocks and constraints. The spatial distribution of PTMA also indicates the energy resilience benefits of certain routes and the potential for public transport improvements.

Minimum travel spend as a percent of household income is a combination of the fuel cost and public transport fare cost for travel to all activities. This builds upon other intermediate outputs of the model, minimum VKT and number of trips by public transport (PT). Fuel cost can be approximated with the current fuel price by the formula shown in **Equation 1**, where  $\eta_{avg, fleet}$  is the average light vehicle fleet fuel efficiency, 10L/100km in New Zealand (MoT, 2011), and the current price is NZ\$2.068 /L (.). Annual household PT cost can similarly be calculated by the formula shown in **Equation 2**; the product of the number of PT trips and the fare price, NZ\$2.30/trip<sup>1</sup> (Environment Canterbury, 2011). The minimum percent of household income spent on transport is then calculated by the formula shown in **Equation 3**; household income is assumed to be the median within the households' census area.

#### Equation 1

$$Annual\_Fuel\_Cost_{HH} = VKT_{HH} \cdot \eta_{avg, fleet} \cdot price_L$$

#### Equation 2

$$Annual\_PT\_Cost_{HH} = Annual\_Trips_{HH} \cdot price_{trip}$$

<sup>1</sup> Assuming up to two trips per day on a concession card.



**Equation 3**

$$\text{Min \% Income} = 100 \cdot \frac{\text{Annual PT Cost}_{HH} + \text{Annual Fuel Cost}_{HH}}{\text{Median Income}_{HH}}$$

Shown spatially, minimum travel spend identifies the distribution of risk to fuel price rises within the urban form. In reality, the annual fuel spend of most households is likely to be higher than the minimum calculated by the model, indicating people currently choose to travel to facilities further than the model assumes, or travel using private motor vehicle in preference to other modes of transport. Of particular note are households where the minimum is not much less than the current transport spend; these households have limited ability to adapt to future energy price rises and consequently are at increased risk to transport energy price rises. As the model is sensitive to land uses and transport networks, the urban form and transport factors that cause certain areas to exhibit lower energy resilience can be determined, and suitable interventions can be highlighted

**Data Requirements**

The model requires:

- The New Zealand Household Travel Survey, from which activity frequencies, mode abilities and saturation values are derived.
- The New Zealand Census, which provides demography and income data. The data is available at two relevant levels, Area Unit, which is approximately the size of a suburb, and Meshblock, which is about four to ten times finer than an Area Unit. However, Area Unit data is preferred, as a significant number of data points are confidentialised at the Meshblock level.
- Destinations as GIS points, grouped by activity classification.
- Household locations.
- Transport networks for:
  - Walking
  - Cycling
  - Public Transport, including walking to/from stops
  - Private Motor Vehicle

The method can be applied to hypothetical data, to test transportation resilience for future land uses or development strategies. This allows accessibility and minimum energy use to be forecast, such that land uses and transport networks can be optimised to provide beneficial outcomes for all members of the community.

**CASE STUDY****Study Area Overview**

Christchurch is the largest city in New Zealand's South Island, with a population of nearly 350,000 people, 120,000 households and a land area of 450 km<sup>2</sup>. This study is based upon Christchurch data prior to the significant earthquakes of September 4<sup>th</sup>, 2010, and February 22<sup>nd</sup>, 2011.

Key Activity Centres<sup>2</sup> are evenly located around the populated areas of the city, mostly within lower income areas, as shown in **Figure 2**. Population density is greatest in a ring around the central city, as shown in **Figure 3**. The central city and west towards the University are predominantly younger, while the fringes of the city are older. Urban Christchurch is

<sup>2</sup> Key activity centres: defined by Environment Canterbury (regional council) as key centres of business and service activity that are highly accessible and constitute nodes on strategic transport corridors (Environment Canterbury 2007).

predominantly flat, and the road network in the central city is laid out in a grid pattern. Christchurch has a comprehensive public transport network of busses, which pass through all the Key Activity Centres. A spatial analysis of the per capita distribution of employment and destinations is shown in Figure 4. Many of the areas with low income in Figure 2 and low population density in Figure 3 are those with a greater number of jobs and destinations per capita, indicating a high level of land use separation. The majority of areas to the south and east of the central city have both low numbers of jobs per capita and few destinations.

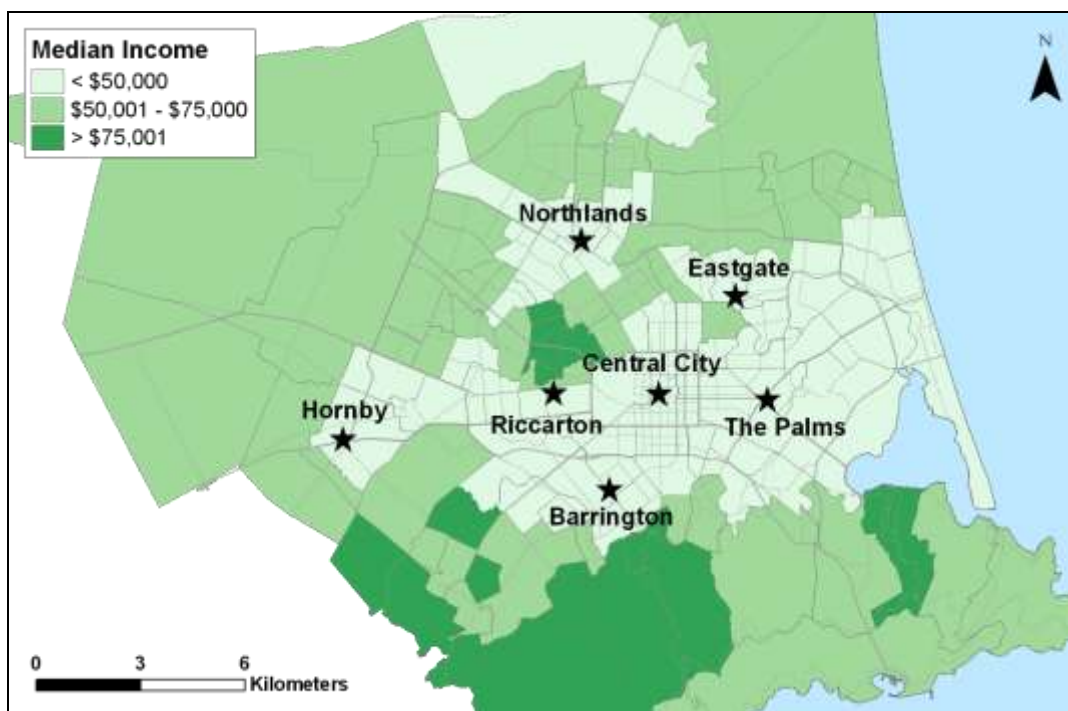


Figure 2 Key Activity Centres and median area income

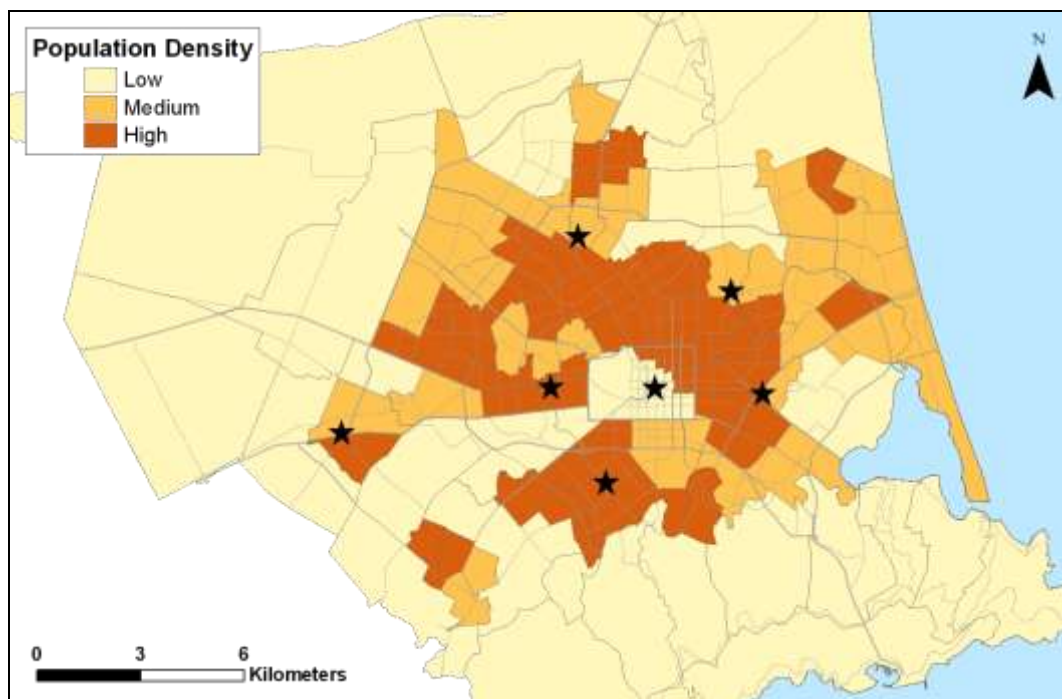
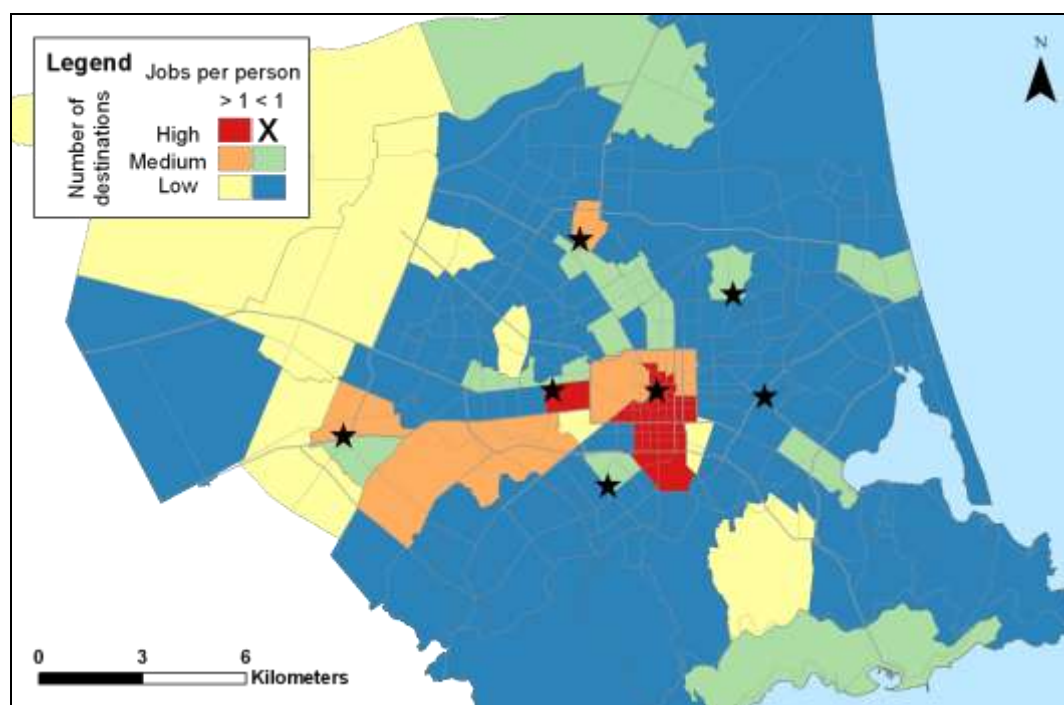


Figure 3: Key Activity Centres and population density

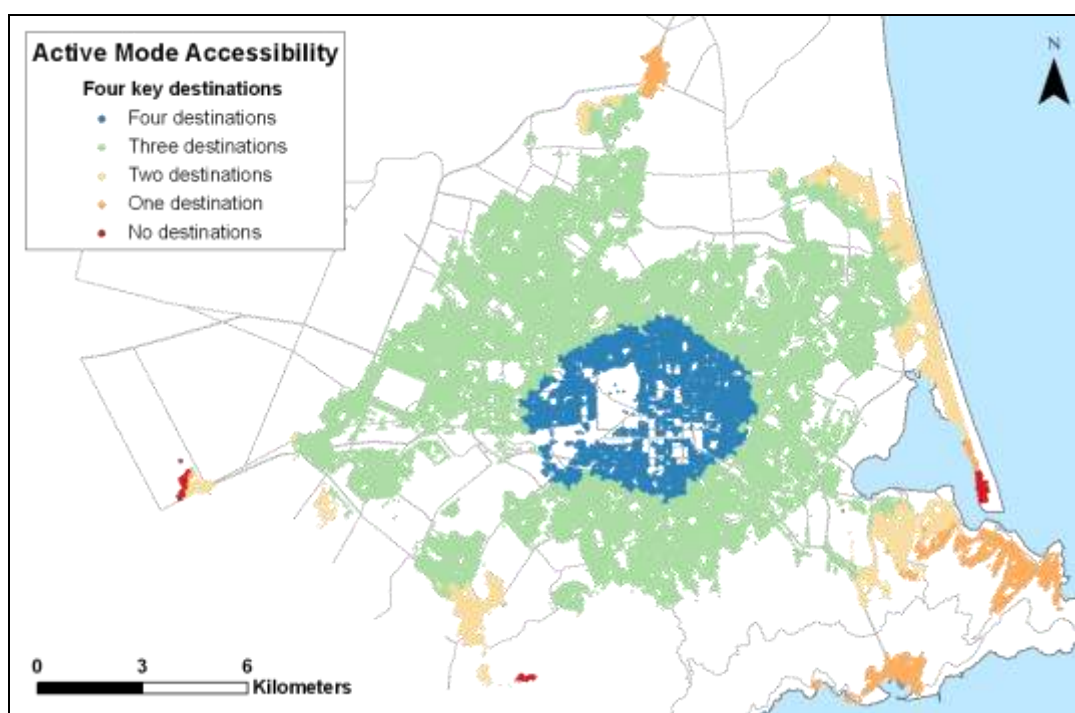


**Figure 4: Comparison of employment density and number of destinations by Census Area Unit. Note: there are no areas with a high number of destinations and less than one job per person.**

## Case Study Results

### Active mode accessibility (AMA)

Most households in central Christchurch have the ability to access all of their four key destinations by walking and cycling, as shown in **Figure 5**, in which each household is represented by a point. Households in and near the city centre have high AMA, as there are a large number of destinations, while accessibility drops markedly at the fringes. Numbers of households within each accessibility category are shown in **Table 4**.



**Figure 5: Spatial distribution of accessibility by active modes of four key activities; Primary/Intermediate School, Secondary School, Shopping and Employment**

**Table 4: AMA results**

Number of key destinations accessible	Number of households	Percent of households
Four	19,495	16%
Three	85,492	71%
Two	10,119	8%
One	4,560	4%
Zero	391	< 1%
	120,057	100%

### Public transport mode accessibility (PTMA)

To understand the contribution of public transport to potential accessibility, the additional accessibility provided by public transport is shown in **Figure 6** and **Table 5**. 17% of all households receive an improvement to their accessibility through the addition of public

transport. Most notably, households around the centre of the city, on or near bus routes, gain access to employment.

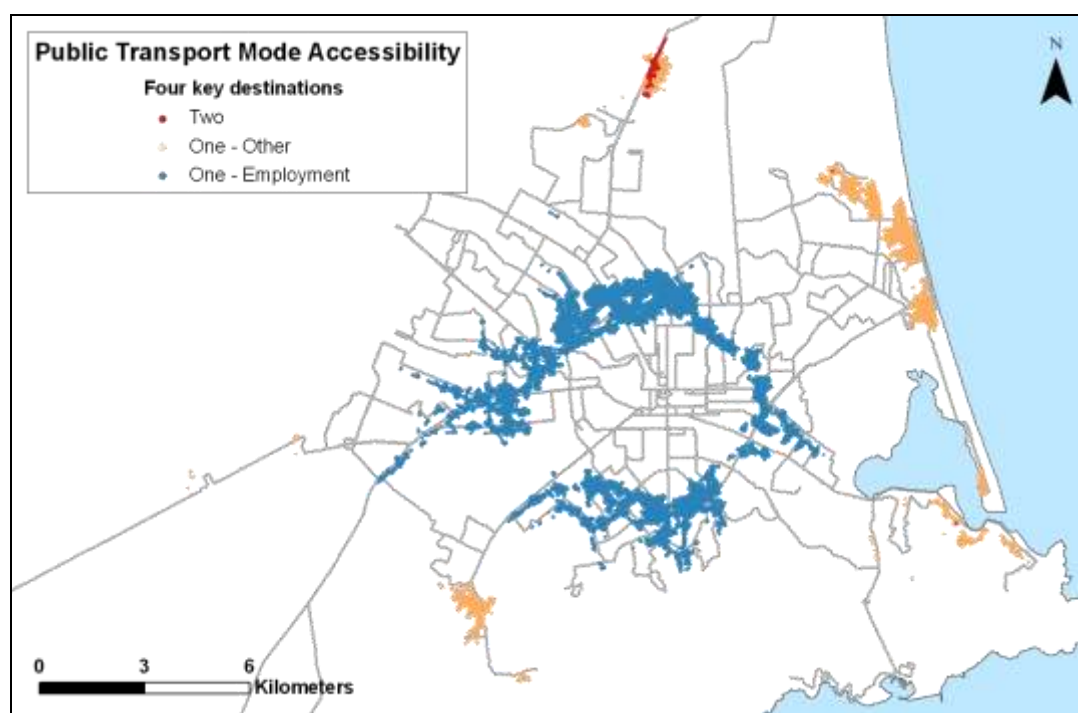


Figure 6: PTMA: additional destinations that can be reached when both Public Transport and Active Modes are used, overlaid on bus routes

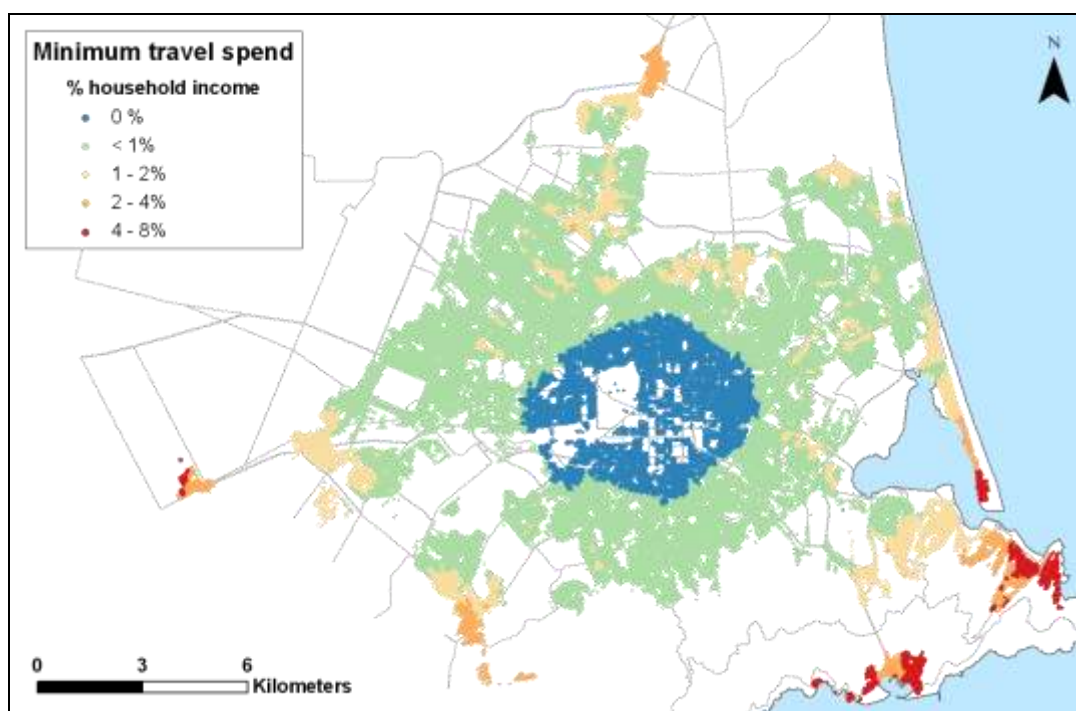
Table 5: PTMA results

Number of additional key destinations accessible	Number of households	Percent of all households
Two	177	<1%
One – other	4,366	4%
One – Employment	15,289	13%
	19,832	17%

### ***Minimum travel spend as a percent of household income***

Household annual minimum travel spends to all activities are calculated from the product of minimum VKT, average fuel efficiency and the current fuel price, the number of bus trips and price, as shown in Equations 1, 2 and 3. The spatial distribution of this value is shown in **Figure 7**, while the number of households within each category are displayed in **Table 6**. As with the results shown in previous figures, households further from their destinations and transport routes are less resilient, and have to spend a greater proportion of their income on transport energy.





**Figure 7: Minimum travel spend as a percent of household income**

**Table 6: Minimum travel spend as a percent of household income results**

Minimum travel spend as a percent of household income	Number of households	Percent of households
0	19,040	16%
< 1%	83,504	69%
1 – 2%	12,106	10%
2 – 4%	3,485	3%
4 – 8%	1,922	2%
	<b>120,057</b>	<b>100%</b>

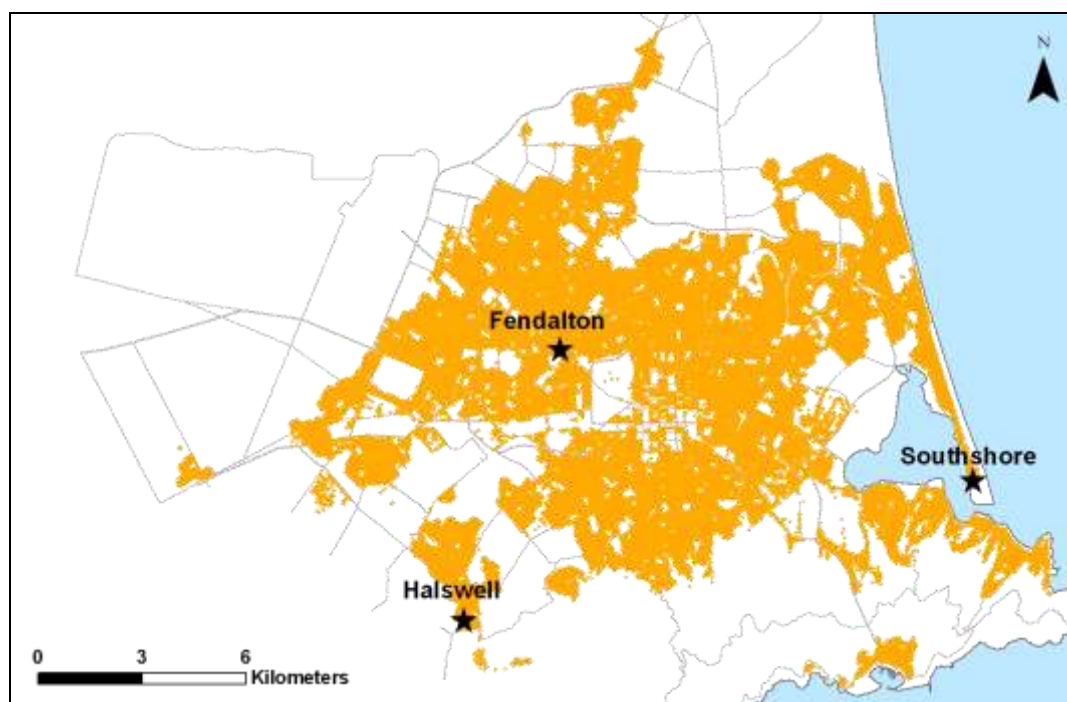
## DISCUSSION

### Macro-Level Resilience Analysis

The majority of the households in urban Christchurch exhibit a high level of energy resilience; 85% of households have the potential to meet all of their travel while spending less than 1% of their income on travel (by both public transport and private vehicle). The highest minimum travel spend required in the study area was 8% of household income. The least resilient households are those on the urban fringes, as they tend to be in lower density areas that are not near destinations nor well served by public transport. Some of these areas are also lower income. The model can also be used to investigate city-wide public transport improvements, which will be discussed in the presentation.

### Micro-Level Resilience Intervention Analysis

Three households, each typical within its area, were selected for resilience analysis and to highlight potential interventions. The households, in Fendalton, Hallswell and Southshore, are shown in context of the rest of the city in **Figure 8**, and general information about each is shown in **Table 7**.



**Figure 8: Households selected for micro-level resilience analysis**

**Table 7: Properties of each of the households**

	Fendalton	Hallswell	Southshore
<b>Income (\$) - census area median</b>	97,000	62,000	49,000
<b>Distance to some destinations (km)</b>	1	1.5	6
<b>Distance to closest major shopping centre (km)</b>	1.5	7	11
<b>Distance to central city (km)</b>	4	10	13
<b>Bus routes &lt; 500m</b>	3	2	1

### **Fendalton**

This household exhibits a large amount of transport choice, as well as a high income which reduces the relative financial effects of increasing fuel prices. The proximity of destinations and employment make it possible that all trips can be met by active modes; consequently, this household is already resilient. Education and Travel Demand Management schemes may assist the household in adapting.

### **Hallswell**

Many trips can be met by active modes and public transport, although the AMA is only two as neither Employment nor Shopping can be fully satisfied by active modes. The current public transport system does not increase accessibility to any of the four key destinations. Improvements to the public transport system, such as express routes directly to the central city or creating suburban hubs from which higher frequency services operate, may increase resilience. Interestingly, as this area is targeted as a future growth node, new shopping (and potential employment) facilities to support the growing population will likely provide many resilience benefits to the existing population.

## Southshore

Due to the isolation of Southshore, and poor transport connectivity to the rest of the city, it forms a worst-case energy resilience scenario. The household has an AMA of zero, as none of the key destinations can be accessed by active modes, although the addition of public transport allows them to reach Primary/Intermediate school. Overall, the household has limited choice for most of the travel they undertake. Simply due to the location, there are few viable resilience interventions; improving active mode links with the nearest shops, about 6km away, may be beneficial but this distance is beyond the active mode ability of the residents (as calculated from the Household Travel Survey). Travel on Demand public transport services may be viable, particularly if they link in to other services at a local hub.

## Further Applications

The outputs of the model can be more generally applied to improving energy resilience outcomes within communities, for example:

- Enhancing the Benefit Cost analysis of proposed walking, cycling and public transport projects. The model inherently considers these modes as a linked system.
- Test the transport resilience impacts of variations in the composition of the private vehicle fleet, to investigate the potential for alternative fuels and increasing vehicle efficiency.
- Optimising the mix of land uses and residential density in mixed use developments.
- Combine with other metrics, such as the Deprivation Index or VAMPIRE score, to analyse areas likely to suffer from transport disadvantage.
- Assess accessibility changes over time due to forecast demographic changes.

Future development of the model will shift travel impedance analysis from a time basis to a cost basis. This will allow the inclusion of proxy measurements for the attractiveness and amenity of active mode and public transport routes, which will further assist in the Benefit Cost analysis of proposed projects.

## CONCLUSIONS

Urban form, transportation networks and travel behaviour are determinants of transport energy demand. The household-level resiliency of transport activity systems to fuel price shocks and supply constraints has not previously been quantified, but has historically been considered low for contemporary western urban forms.

This paper introduces the *minimum energy potential* as an extension to the NZ Transport Agency accessibility modelling methodology developed by Abley Transportation Consultants. It is a measure of household-level energy (fuel) price resilience assessed at the city scale that can be implemented using GIS and Census data. The minimum potential for a household is a function of the age demography of the resident population, the proximity of destinations and the viability of active modes and public transport. The minimum potential contributes both an important new understanding to future transport and land-use planning, and a quantifiable measure of transport energy resilience.

Results of the case study investigated in this paper indicate that many of the residents of urban Christchurch exhibit a high level of energy resilience; 85% of households have the potential to meet all of their travel while spending 1% or less of their income. This is due to the high connectivity of transport networks and proximity of destinations for most households. Residents of the urban fringes tend to exhibit lower resilience as they have to travel further to reach their destinations, and have no option within the model other than to divert a greater



portion of their income to meeting transport energy needs<sup>3</sup>. The model can be used at a range of levels to identify potential resilience interventions, as well as test proposed future land uses, demographic forecasts or specific developments.

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<sup>3</sup> These residents may have made a conscious decision that the 'costs' of increased travel times and expenses are worth the lifestyle benefits of living in their chosen location.

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***B.2.2.1 Review results***

Ensure key points of methodology and conclusions are not lost in finer detail in presentation which requires some abbreviation. Suggest elaborating on uses described in ‘Further Applications’ and Conclusions.

**B.3 Conference presentations**

During the thesis the research has been presented at a number of national and international conferences:

1. **New Zealand Society for Sustainability Engineering and Science (NZ-SSES)** conference; December 2010, Auckland
2. **Transportation Research Board (TRB)** 90<sup>th</sup> annual meeting; January 2011, Washington D.C.
3. **Institute of Professional Engineers New Zealand (IPENZ) Transportation Group** conference; March 2011, Auckland
4. **Australian Institute of Traffic Planning and Management** conference; August 2011, Melbourne
5. **New Zealand Surveying & Spatial Sciences** conference (SSSC); November 2011, Wellington
6. **IPENZ Transportation Group** conference; March 2012, Rotorua